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Development and Demonstration of Concepts for Improving Coke-Oven Door Seals

Battelle Columbus Labs., OH

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FINAL REPORT

on

DEVELOPMENT AND DEMONSTRATION OF CONCEPTS FOR IMPROVING COKE-OVEN DOOR SEALS

to

METALLURGICAL PROCESSES BRANCH
INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY
UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
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16. ABSTRACT The report discusses the design, laboratory scale tests, construction, and field tests of an improved metal-to-metal seal for coke-oven end doors. Basic features of the seal are: high-strength temperature-resistant steel capable of 3 times the deflection of current seals without permanent deformation; no backup springs and plungers and the attendant requirement for manual inservice adjustments; seal installed to conform to the jamb profile; seal lip height reduced to give 8 times the inplane flexibility; and compatibility with existing coke batteries and door handling machines. Field tests on operating 4 and 6 m batteries proved the soundness of the concept along the straight vertical sides of the door. However, an unforseen force combination in the four corners resulted in a net force acting to lift the seal corners away from the jamb, resulting in unacceptable leakage at each seal corner. Various schemes were evaluated empirically in an attempt to understand and solve the problem. A modified design to eliminate the problem and reduce fabrication cost is proposed. Inland Steel Company plans to build and test the modified design at its own expense. This was a jointly funded EPA/American Iron and Steel Institute project.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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Coking	Stationary Sources	13H
Ovens	Coke Oven Door Seals	13A
Doors		13M
Seals		11A
Iron and Steel Industry		11F

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EXECUTIVE SUMMARY

ORIGIN

In 1975 Battelle completed a project entitled "Study of Concepts for Minimizing Emissions from Coke-Oven Door Seals". This project was jointly sponsored by the Industrial Environmental Research Laboratory of EPA and the American Iron and Steel Institute (AISI).

The results and recommendations of the 1975 study were accepted by both sponsoring organizations and late in 1976 Battelle was awarded research contracts (with EPA and the AISI) dealing with development/engineering/laboratory evaluation of the recommended, upgraded metal seal. The results of this effort were accepted by the sponsors and funding was made available to complete Phase III of the program which consisted of fabrication and field demonstration of the recommended seal design/material.

THIS REPORT

Included in this report is a summary of the entire effort devoted toward the objective of an upgraded, retrofittable, metal coke-door seal. "Upgraded" in this instance is defined as having significantly improved performance in emission control and operation.

Not included in this report are the results of the major effort completed on preventing/minimizing warpage of coke-oven jambs by effecting changes in the jamb design and materials. This work was, however, reported in a formal interim report issued in July of 1978.(1)

THE RECOMMENDED SEAL DESIGN/MATERIAL

The recommended seal design was the result of finding a best "fit" as evaluated by a long list of criteria and specifications. In a systematic approach, each criterion had to be considered but the two major influences on the design were (a) a general specification by the AISI and EPA, and (b) a criterion strongly desired by Battelle researchers.

The major specification was that the new seal be retrofittable, i.e., the new seal would be a replacement for the existing seal designs without modification of the doors or the door-handling equipment. This also meant that the recommended seal had to "handle" or accommodate all (or nearly all) of the jamb and the door warpage problems that exist at operational plants. Seals are attached to doors and the profile congruency of the door with the oven jamb can be poor due to past warpage and heat effects.

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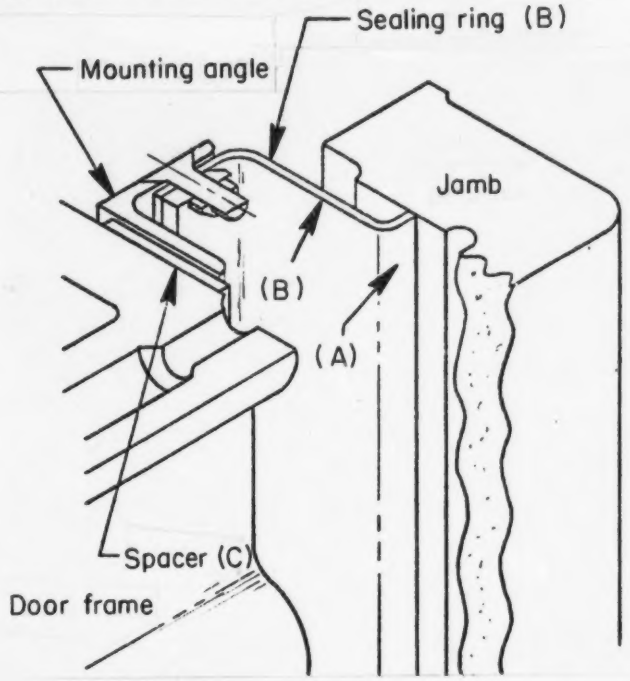
(1) Development and Demonstration of Concepts for Improving Coke-Oven Door Seals: Interim Report EPA-600/2-78-189.

The criterion desired by Battelle personnel was that the recommended design/material should eliminate the need for numerous, manual seal-adjustment devices associated with all of the existing seal designs. With about 25,000 coke-oven doors in operation, each with about 20 manual, seal-adjustment devices; the theory is that at times workers climbing ladders or scaffolds would adjust 500,000 devices to improve emission control. Battelle researchers were skeptical about the performance of the adjustment devices and the availability of the time and skill to manipulate these devices.

The general approach to an upgraded seal was to increase the seal flexibility in every way possible while also increasing the strength and heat resistance of the seal. This approach resulted in the recommended design shown in cross section below.



CROSS SECTION OF A SUGGESTED NEW COKE-OVEN SEAL DESIGN

The design/material elements leading to increased flexibility and strength are as follows:

1. The height of the contacting edge [marked (A) in the above drawing] was lowered to a 9.5-mm height (from 19 mm) to increase the flexibility of the edge along the jamb by a factor of 8. This increased flexibility allowed the vertical seal edge to maintain contact with the jamb in spite of curvatures in the jamb surface and the uneven surface of the seal edge.
2. The main spring element [marked (B) in the above drawing] was switched from 304 stainless or a corrosion-resistant, low alloy steel to a high-strength, high-temperature spring alloy. Battelle recommended that the first demonstration seals be made of age hardened Inconel X-750. In laboratory tests at 426 C (800 F), Inconel X-750 tolerated three

times the amount of seal deflection during simulated door latching before plastic distortion by creeping was encountered. Increased seal deflection is desired to (a) absorb minor changes in door and jamb profiles without the need for adjustments, and (b) keep an evenly distributed force pressing the seal edge against the jamb.

3. Changing the width of the spacers [marked (C) in the above drawing] along the door made it possible (during original seal mounting) to bend the entire seal to make the profile of the seal edge match the general profile of the jamb. This element of flexibility was introduced to make it possible to realign the seal edge and jamb profile in instances where the door and jamb profiles are particularly incongruent.

This design eliminated the need for seal-adjustment devices (and backup springs) pressing in point loading against the outboard side of the seal.

DEMONSTRATION SEAL FABRICATION

Two of the criteria for judging seal designs were (a) whether the design was amenable to mass production methods, and (b) whether the machining during fabrication could be eliminated. For the design presented, Battelle recommended (1) roll forming the seal shape rather than one-at-a-time brake forming, and (2) hydroforming the corners rather than the cut-fit-weld-machine fabrication methods now being used. This approach did not endear the design or the researchers with the standard fabricators of conventional coke-door seals. Further complications were introduced when:

- The Coke Practice Committee of the AISI insisted that demonstration seals should be obtained from the present seal suppliers(1) rather than jobbing parts of the fabrication to different smaller shops.
- Battelle introduced a seal-corner design that could only be fabricated in a hydroforming operation.

Eleven months after sending out requests for quotation for demonstration seals, four seals were delivered to the Bethlehem Steel coke plant in Lackawanna, New York. The special effort made by Bethlehem Steel to obtain these seals is described in the acknowledgment section of this report.

RESULTS OF THE SEAL DEMONSTRATION EFFORTS

Test work with the recommended seal design/material was done at Bethlehem Steel's coke plant in Lackawanna, New York (6-meter Wilputte battery) and at Republic Steel's coke plant in Youngstown, Ohio (4-meter Koppers batteries).

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(1) The source of this insistence was the purchasing departments of steel companies that wanted "standard, known suppliers" and "one bill for one shipment".

At Lackawanna it was possible to demonstrate the usefulness of (a) taking simple measurements of the variation in distance between the jamb and door (along its length) and then installing spacers under the new seal to bring the seal edge into congruency with badly warped jambs. In one instance it was necessary to put a 19-mm (3/4-inch) steel bar under the top, horizontal portion of the seal to bring the profile of the seal into alignment.

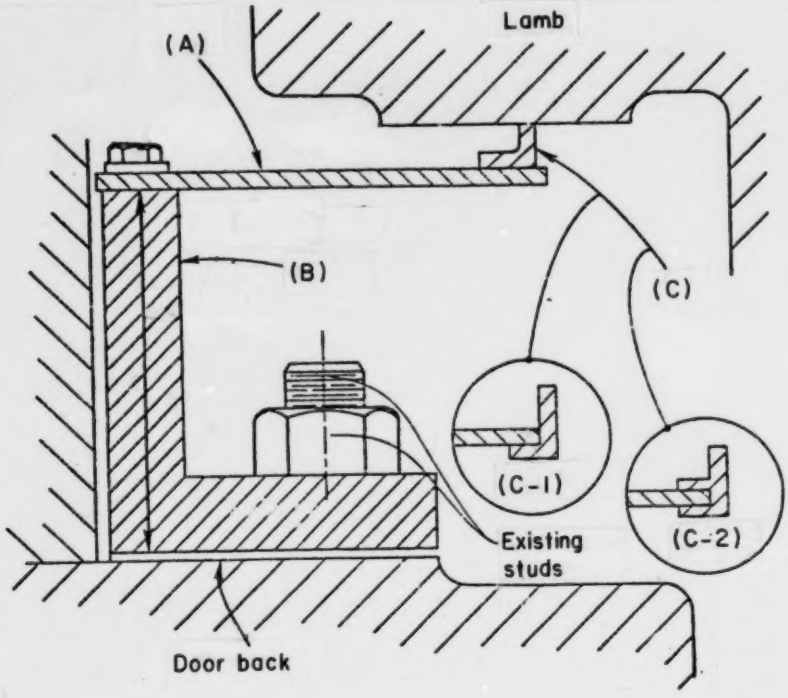
Zero leakage, increased flexibility, and no manual adjustments were demonstrated (for months) along the 6-meter vertical sides of the seal, as expected.

However, all four seals put into operation unexpectedly released emissions through gaps at each corner. This problem persisted even after "reworking" one seal to eliminate variations in the flatness of the seal edge. It was deduced that the corners were "lifting off" the jamb, i.e., the corners were reacting to forces that act to cause a slight gap at the corners during seal deflection. This "lift off" effect was confirmed at Republic Steel during test work completed using a 4-meter seal forced against a flat machinist table.

The fact that corners on seals can react counter to a desired pattern was not new information — U.S. Steel research personnel had graciously told Battelle about "corner lifting" they had encountered on standard seals. What was obvious was that (a) the design changes made to avoid this potential problem were not successful in full-scale operation, and (b) that Battelle's laboratory work on parts of the seal did not model the reactions in complete seals. Experimental work completed at Republic Steel indicated that the seal lip was not part of the problem and that some method had to be found to relieve the "bunch-up of metal" that occurs during the seal deflection in the flat portion of the seal in the corners.

THE NEW SEAL DESIGN

This project was not funded with the idea that a considerable amount of problem solving would be required after getting the first demonstration results. Although continued analytical work was considered (modelling and strain gauge testing on a full-scale seal), the last emphasis in the project was to consider the range of design changes that could provide an empirical solution to the corner problem. Out of this approach came a revised seal design (not as yet tested). This new or modified design is shown in cross section in the following drawing.



Shown in this drawing are the major elements:

A is a flat strip, cantilever-spring replacement for the formed S-shape used in the original design.

B is a heavy-section, carbon-steel, angle-iron seal holder.

C is a demountable seal-edge angle bolted or welded to the seal element (no machining required).

It is recommended that the spring portion of the seal be made of 17-4 PH stainless steel rather than Inconel X-750. This lower priced alloy was not included for consideration in the original evaluation because it is a difficult alloy to form, but all forming is eliminated in this design. It is expected that this seal can be built by steel companies.

For an empirical approach to a solution of the corner problem, it is suggested that the strips making up the main portion of the seal be only butted at the corners and not welded. This leaves a space or separation in the corner that (a) makes the corner relatively flexible, (b) permits consideration of corner backup-springs outboard of the corner to force the corner against the jambs, (c) may minimize some of the stress generation in the corners during deflection, and (d) could introduce a built-in emission problem in the corners. To prevent emissions through the spacings, it is suggested that this space be closed with a cover strip (or foil) attached outboard of the corner.

PRESENT STATUS OF THE NEW SEAL

Inland Steel has volunteered to engineer/fabricate/test and oven demonstrate one seal of the new design. At this time, the engineering is complete and fabrication is in progress.

CHAPTER I

INTRODUCTION

This report summarizes the development and demonstration stages of a project entitled "Development and Demonstration of Concepts for Improving Coke-Oven Door Seals". Although the primary objective of this project was to develop a retrofittable metal-contact seal, a considerable effort was involved in the secondary objectives of improving the design and material of jambs to minimizing the future warping of this important part of coke-oven end closures. A description of the secondary effort and results was not included in this report because this has been previously reported.(1)

The work reported herein was sponsored by the Industrial Environmental Research Laboratory of the EPA and by the American Iron and Steel Institute (AISI). As per contractual agreement, the purchasing cost of the demonstration seals fell entirely upon several companies and this is noted in the acknowledgments section of this introduction.

Background and Antecedents

In January of 1974, the Battelle-Columbus Laboratories responded to an EPA Request for Proposal (EPA RFP No. DU 74-A039) dealing with a research project to study, innovate, and evaluate concepts for minimizing emissions from coke-oven door seals. It was understood that the research would be sponsored and financed jointly by EPA and the AISI and that the research was to be monitored by EPA.

After competitive bidding, the contract for this research project was awarded to Battelle-Columbus in June 1974. This research project followed the plan outlined in the RFP and was entitled "Study of Concepts for Minimizing Emissions from Coke-Oven Door Seals". The approved final report was issued in July of 1975. Copies of this report are available from the National Technical Information Service (NTIS) as Document PB 245580.* This report is reference material for the present project.

The conclusions of what came to be called the "Concepts Project" were as follows:

- Of all the concepts considered, Battelle researchers rated upgraded metal-to-metal seals as the best retrofittable approach to minimizing the emission problems from

(1) Development and Demonstration of Concepts for Improving Coke-Oven Door Seals: Interim Report EPA-600/2-78-189.

*The address of the NTIS is 5285 Port Royal Road, Springfield, Virginia 22161.

coke-oven door seals. Only upgraded metal seals were given a rating indicating a 90 to 100 percent probability of successful development and successful performance within the criteria specified jointly by the EPA and the AISI.

- Upgraded metal-to-metal seals should be:
  - (a) more flexible in terms of conforming to large distortions in jamb profiles
  - (b) more heat resistant to minimize plastic deformations under load at temperatures to 426 C (800 F)
  - (c) more conforming to warped jambs and changes in jamb profiles without the need for periodic adjustments by coke-plant workers.

In January of 1976, Battelle-Columbus was asked by the EPA/AISI (EPA RFP No. DU-76-A103) to present a proposal and a series of recommendations dealing with "Development and Demonstration of Concepts for Improving Coke-Oven Door Seals". This proposal was to be based on the conclusions and recommendations of the July 1975 Concepts Study. As given above, the title of the possible new project was somewhat of an understatement because the sponsors were interested in research and development of all aspects of end closures that relate directly or indirectly to emission control. Battelle-Columbus presented a proposal that was responsive to the following points:

(a) Follows through and develops further the conclusions and recommendations of the Concepts report

(b) Schedules arrangements to present our results and recommendations for the Phase III demonstration prior to the end of the project for critique by the EPA, members of the AISI and their research organizations, and other interested organizations. This critique period allows time for evaluation by the sponsors as to whether the follow-on demonstration project should be funded, and allows continuation of the overall program without interruptions between major phases

(c) Takes into consideration and makes use of the end-closure and emission-control data to be supplied by several large steel company research laboratories. Battelle researchers were also to obtain measurement data, but were to make independent conclusions and recommendations

(d) Defers plant testing of recommended seals, jambs, doors, and other end-closure components until given technical and administrative clearance by EPA and AISI to do so.

Our proposal was accepted and a contract was awarded in August of 1976. The development work, including engineering drawings of our proposed designs, was to be completed by the end of August, 1978.

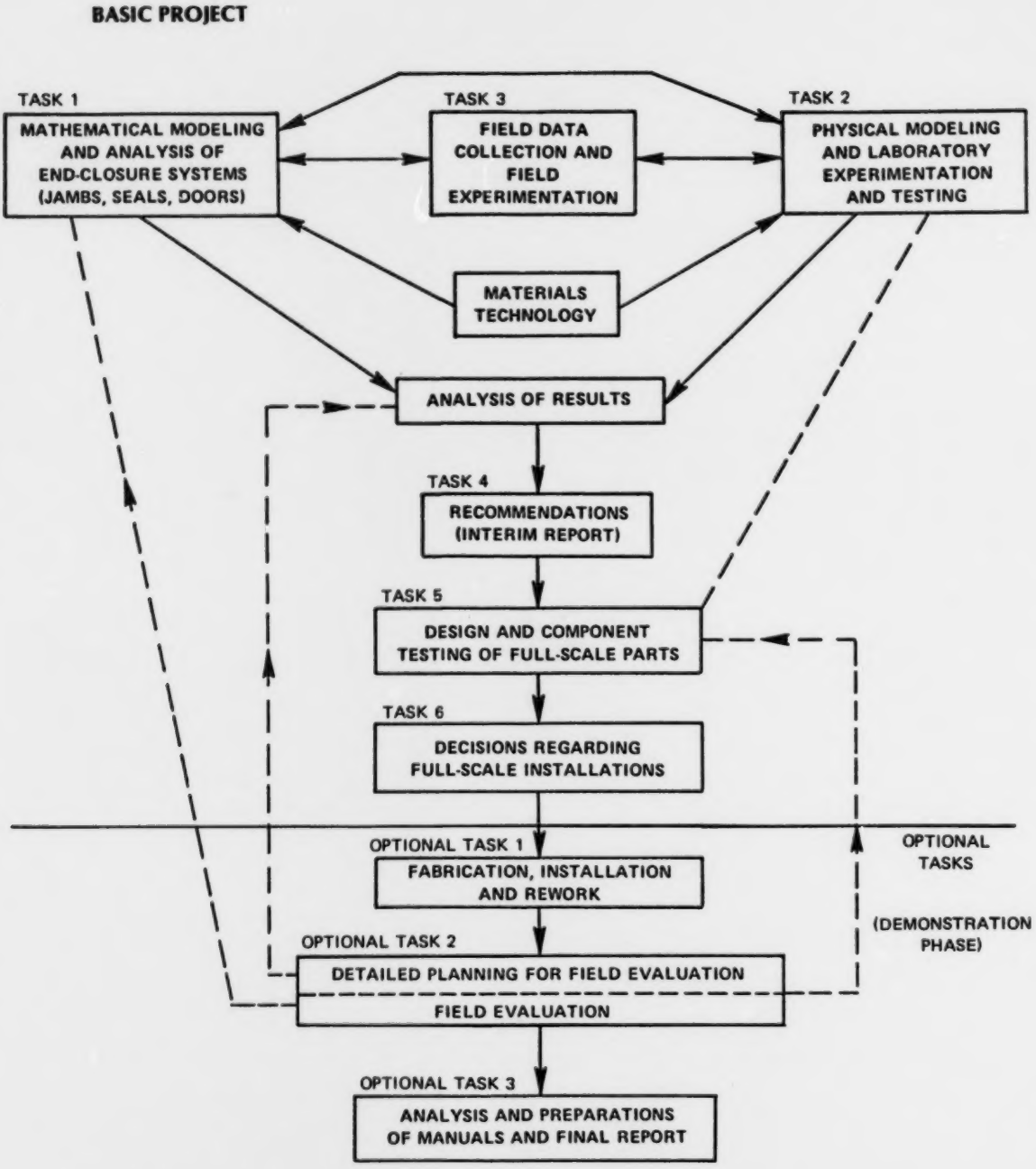


FIGURE I-1. OUTLINE OF ACTIVITIES IN THE EPA/AISI RESEARCH PROGRAM ON IMPROVED SYSTEMS FOR SEALING COKE-OVEN END CLOSURES

This research was conducted by coordinating the efforts of researchers within three Departments at Battelle:

(1) Metallurgy Department

(2) Structures and Mechanics Research Department

(3) Engineering and Manufacturing Technology Department.

The key or lead personnel within the three departments are as follows:

A. O. Hoffman, Project Manager, Metallurgy Department

A. T. Hopper, Leader of the analytical effort, Structures and Mechanics Department

R. L. Paul, Leader of the design effort, Engineering and Manufacturing Department.

The sponsorship personnel most directly concerned with this study are:

Mr. Robert C. McCrillis, Project Officer for EPA

Mr. John G. Munson, Jr., Project Officer for AISI (now retired)

Mr. Richard G. Phelps, Project Officer for AISI

Mr. Calvin Cooley, AISI Headquarters, Washington, D. C.

Mr. George C. Bennett, Contract Administrator for EPA

Mr. M. P. Huneycutt, Contracting Officer for EPA.

Contents of This Report

This final report consists of:

- An abstract of the seal portion of the Interim Report
- A summary of Tasks 5 and 6 dealing with seal design and laboratory testing of the seal
- A summary of Optional Task 1 (Fabrication, Installation, and Rework)
- A summary of the field results and Evaluations.

Acknowledgments

A complete list of acknowledgments of the companies, organizations, and helpful individuals, within the steel industry and EPA, that contributed significantly to this program would be lengthy. Rather than take the risk of inadvertent omission(s), we have shortened our acknowledgments list to the following:

1. The assistance given to us at many coke plants (not all) where we elected to obtain detailed measurements.
2. The generosity of the United States Steel Corporation research organization for furnishing their internal technical report entitled "Coke Oven–Door System Technology: Field Data From Clairton Works". We were fortunate in being able to quote from this report and having discussions with the USS team.

3. The cooperation of Bethlehem Steel and Republic Steel's management in:
   (a) offering one or more of their coke plants for demonstration testing
   (b) purchasing demonstration seals under what was excessively expensive conditions (learning period for fabricators)
   (c) paying for the rework of unsatisfactorily manufactured seals
   (d) assigning Engineering Department personnel to assist the project.
4. A special acknowledgment must be given to Bethlehem Steel Corporation in expediting the fabrication of the first four demonstration seals. Until Bethlehem Steel took action, the fabrication portion of this project was stalled for almost a year, while the two selected fabricators took the position that "we will bid after the other company bids". Without waiting for continued grouping of orders from various steel companies to reach a fabrication quantity that would interest fabricators, Bethlehem Steel (a) obtained the selected alloy material, (b) ordered the special tooling required for hydroforming of the seal corners (an improved, machine-production operation), and (c) "convinced" a fabricator to complete the order. This action on the part of Bethlehem Steel Corporation broke the "log-jamb" and moved the demonstration project forward.
5. The Project Officers (Mr. McCrillis–EPA, and Mr. Phelps–AISI) functioned as an organized and responsive team with regard to this project. We particularly appreciate the support, guidance, and counsel given to us by these gentlemen.

CHAPTER II

SUMMARY OF THE ANALYTICAL PHASE DEALING WITH UPGRADED METAL SEALS

This chapter is an extract of the analytical phase of the development project dealing with upgraded metal seals.

Description of Existing, Standard Coke-Oven Door Seals (With Comments)

Of the coke-oven batteries that have metal-to-metal seals on their doors, about 25 percent have the fixed-edge design shown in Figures II-1 and II-2. About 70 percent have the S-shaped design shown in Figures II-3 and II-4.

Discussion of Fixed-Edge Seal System

The latch force pressing the fixed-edge seal against the jamb is generated by a door-mounted spring system. Because the latch forces "clamp" the jamb and the door together, this system is self-balanced. The total contact force between the seal and the jamb equals the latch force. Another feature is the rigidity of the seal. Rigidity in this context does not refer to the resistance of the seal edge to bending (although this is present in these designs), but rather to the fact that these seals lack capability for automatic adjustment to small changes in the profiles of the jamb or door. This feature of the rigid sealing system manifests itself in the development of leaks and in a nonuniform sealing pressure around the seal, i.e., the contact pressure between the seal and the jamb is different at one place on the seal than another. This is depicted in Figure II-5 where the sealing pressure is shown to be significantly higher under the latches than between the latches. Once contact has been made between the seal and the jamb at the latching levels, increasing the latch pressure will increase the sealing pressure only under the latches. Thus, if the seal is leaking elsewhere, only manual adjustments near the leak can cure the situation.

The two points made so far – uneven sealing pressure and low effectiveness of increase in the latch force – are easily envisioned by taking two yardsticks and squeezing them together at two locations. This is depicted in Figure II-6. The pressure between the edges of the rules will clearly be higher at the locations where the rules are being squeezed together than say between the clamps. Moreover, squeezing harder will make little or no change in the contact pressure at locations between the "latch levels".

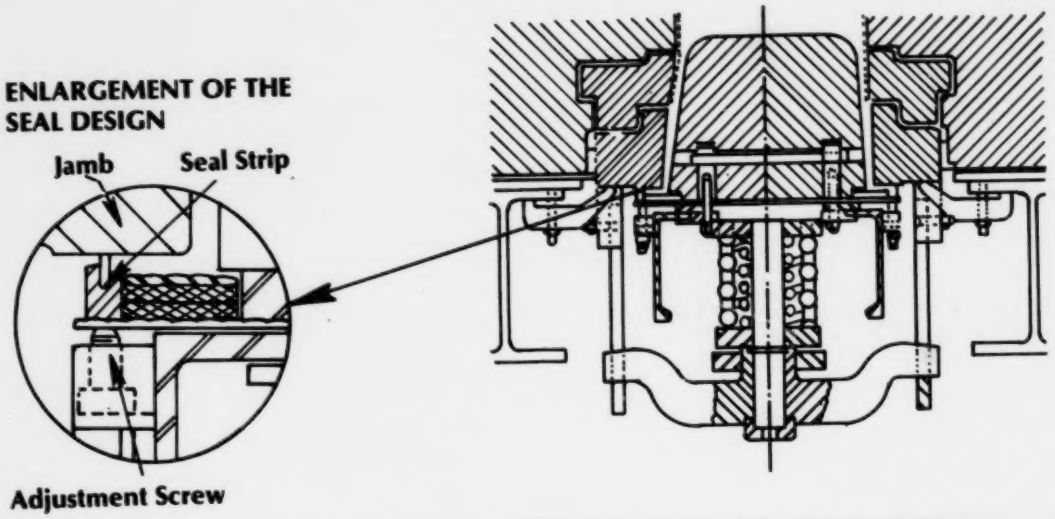


FIGURE II-1. CROSS SECTION OF A TYPICAL COKE-OVEN DOOR WITH A FIXED-EDGE SEAL

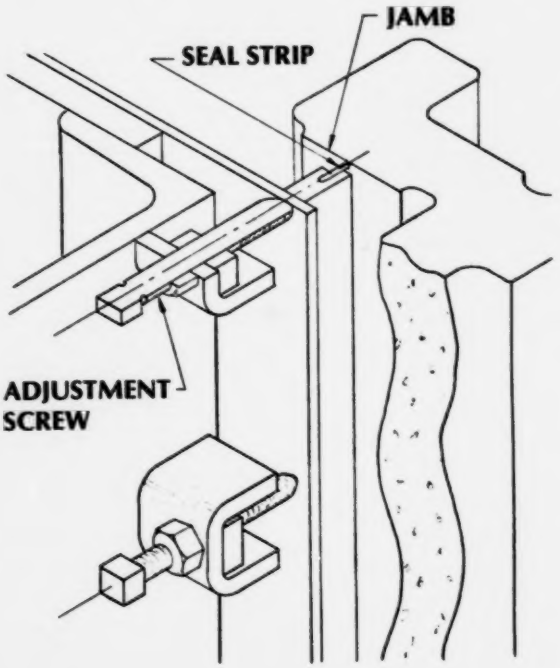


FIGURE II-2. SIDE VIEW OF ADJUSTMENT EQUIPMENT ON FIXED-EDGE SEALS

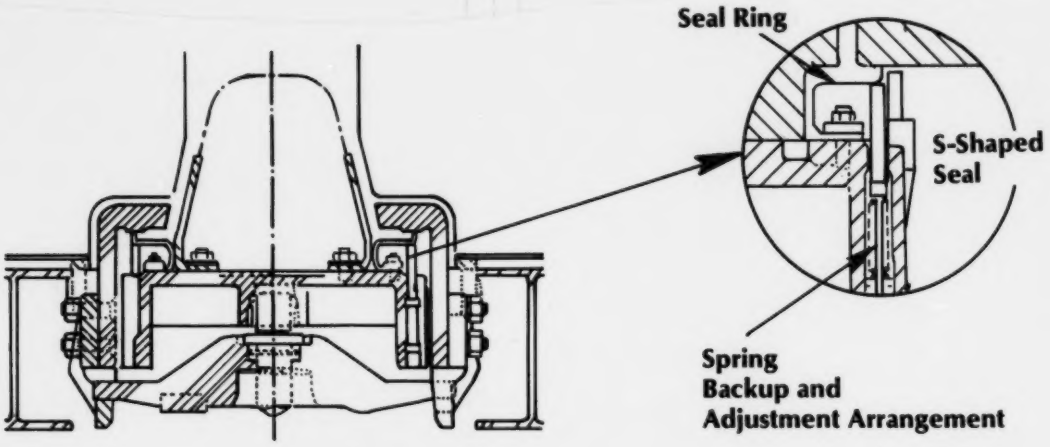


FIGURE II-3. CROSS SECTION OF A TYPICAL COKE-OVEN DOOR WITH AN S-SHAPED SEAL

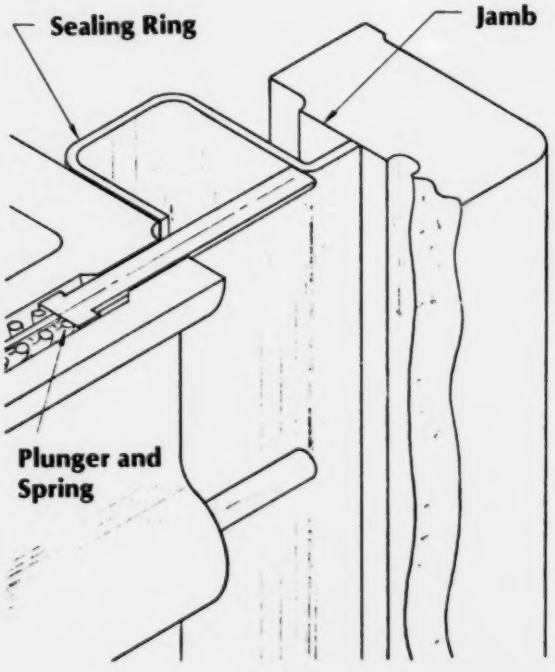


FIGURE II-4. SIDE VIEW OF S-SHAPED SEAL SYSTEM

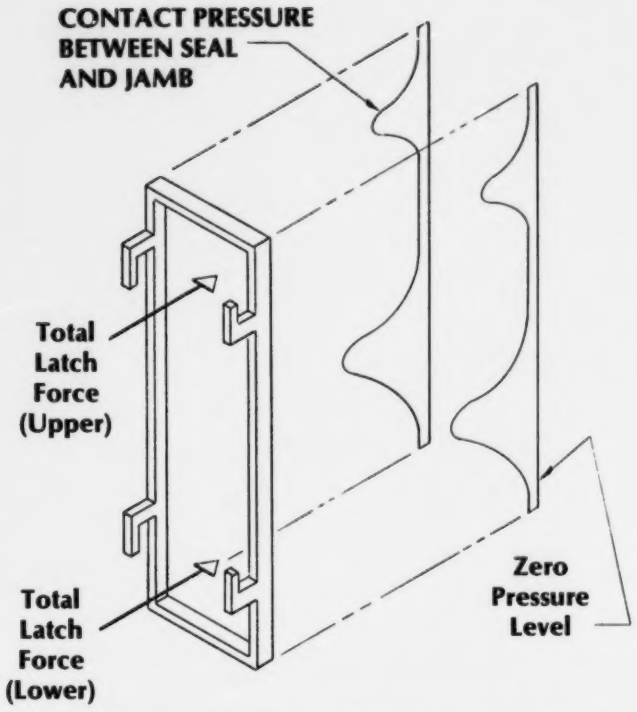


FIGURE II-5. DISTRIBUTION OF CONTACT (SEALING) PRESSURE

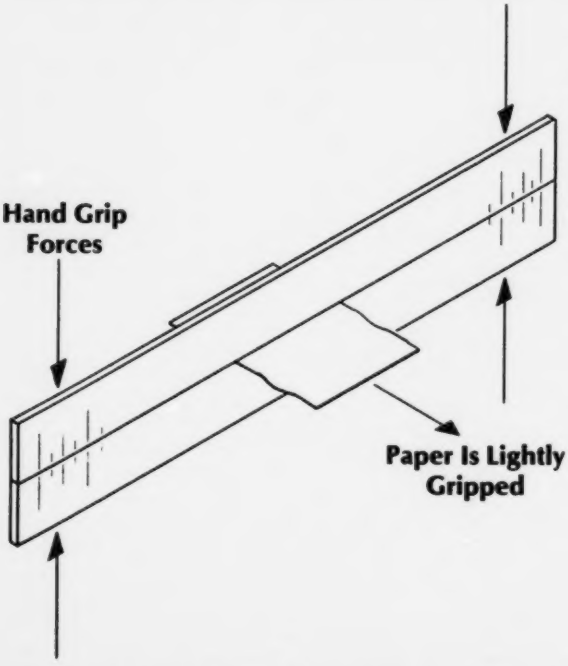


FIGURE II-6. AN EXAGGERATED REPRESENTATION OF THE CONTACT PRESSURE DISTRIBUTION BETWEEN TWO CLAMPED RULES

Because of the preceding two points, and because the rigid seals cannot of themselves assume a different contour, rigid seals are susceptible to development of leaks if a slight change in the contour of the jamb or door arises because, for example, of changes in thermal gradients. Such leaks can be stopped only by adjusting the seal manually with the available devices. Adjustments to the seal while the door is in place can have several possible consequences, each of which needs to be considered.

Recall from preceding discussions that the latch force is distributed around the seal/jamb interface as a contact pressure which we have referred to as the sealing-pressure distribution. The total latch force equals the sum of the contact force around the seal perimeter. Any manual adjustment to the seal is made with the intent of changing the seal pressure somewhere around the seal, most probably to increase it from zero where a leak is occurring. Thus, any adjustment will either increase, leave unchanged, or decrease the total latch force and will redistribute the seal pressure. Because intuition says that if there is a leak there is a gap, and, if the seal edge needs to be advanced to close the gap, most adjustments will result in an increase in the latch force. Note that it is not inconceivable that a gap could be closed by loosening the appropriate adjustments but to know how to do this requires skill and experience.

If the latch force is increased by adjustments made to the seal while the door is in place, in the fixed-edge systems this implies that the main latch springs are compressed further and the door main body is a bit farther from the jamb. This design can reproduce this increased latch force on the next placement of the door provided the springs are not fully compressed through relaxation or through damage from fires.

The fixed-edge designs have two distinct positive features which need to be emphasized. One of these is the point just made that the springed latching force has the ability to increase and decrease as fine adjustments are made to the seal and, more importantly, the ability to reproduce this new sealing force automatically. The other advantageous feature is the way in which the entire seal element is adjusted by moving it back and forth. These features are recognized as important and will be discussed again relative to our recommendations.

Discussion of S-Shaped Seal System

The S-shaped seal system shown in Figures II-3 and II-4 has a more flexible sealing element and is backed up by springed plungers spaced about every 20 to 25 cm (8 to 10 inches) around the seal. These devices give adjustability but with the retention of flexibility at the seal edge. The latch force in this system is usually applied by a screw mechanism that is motor driven and cuts off by means of a current limiter to the drive motor. The motor and drive are a part of the door-handling equipment. One other feature of this system which does not show in the figures is the presence of

stops to keep the door from advancing so far as to overstress the seal. These stops are at the corners of the doors on 4-meter ovens and at the corners and two places in between on the taller 6-meter ovens.

The important differences between this system and the rigid seal systems are in the latch-force devices and in the seal design. Because of the way the latch force is generated on the S-shaped seal system, it will not respond to adjustments in the manner described previously for the rigid seals. Here, with the door in place, adjustments to the seal will again most probably increase the latch force above what was present on placing the door. Assuming the latch force to be increased in this way, when the door is removed for pushing and then replaced, the door-handling machine will essentially reproduce the previous lower latch force. This will cause still another distribution of latching force. If leaks occur, adjustments will increase the latch force once more to a level which cannot be reproduced by the drive motor when the door is placed in the next cycle.

The difficulty with the more flexible S-shaped seal system can be overcome by incorporating a spring-latch system and a spring seal.

These are advantages of the flexible seal worth noting. Flexibility is used in this discussion to mean the ability to flex or to bend in a spring-type fashion. Thus, the flexible seal can automatically adjust to small changes in the jamb or door profile without losing sealing pressure. Flexibility also means that the sealing pressure at any point can be about the same as at any other point – that is, the sealing pressure can, in theory, be relatively uniform around the door. A final advantage which can be expected but which is not quite so obvious is that, for a given latch force, the flexible seal is capable of sealing a greater mismatch between the contours of the seal and the jamb. While this was expected, the mathematical analysis indicated that the difference is more than minor.

Up until this point in our discussion, the topics have been limited to features which were particular to either the rigid or to the flexible seals. Certain features which they have in common are also worthy of mention. One way a seal edge can be permanently damaged is by subjecting it to a force which develops stresses in excess of its yield strength – a property of the material. Both flexible and rigid seals are easily damaged if they are banged against the jamb or against the latch hooks by the door-handling machinery. But there are other and more subtle ways of damaging a seal by overstressing. Both of the sealing-system designs have a common feature that is undesirable and which the research team has termed "point loading". Referring to the drawings of the various designs, it is clear that each seal is affected from the rear by screws or spring-loaded plungers. Each device applies a force at a small area at the back of the seal. The difficulty with point loading is that it causes a stress concentration, particularly on the more flexible S-shaped seal. Overstressing the seal at such a point can result in damage by yielding or in dimensional changes resulting from creep and relaxation. In addition, *point loading does not necessarily guarantee distribution of the load between the points of force application.* In this regard, the situation is somewhat similar to that described in the previous discussion concerning latch-force distribution with fixed-edge seals.

It is for these reasons that it was recommended to the design researchers that consideration should be given to the elimination of point loading on the rear of seals. This recommendation was considered to be particularly important where the seal system is to have a high degree of flexibility.

A more difficult similarity to discuss is the yielding of the seal member through bending. The rigid seals are bent as a unit. The entire rigid seal is bent or deflected to attempt to conform to the jamb contour. Flexible seals, on the other hand, are bent in a rather complicated way. The rear of the seal is attached to the body of the door and thus has the same contour as the door. The sealing edge, on the other hand, is loaded by plungers and bends in a way that may be contrary to the rear of the seal. Thus the seal is being asked to contort in ways which may cause it to yield permanently. The analysis in the Task I effort also showed that the amount of forward or backward adjustment of the spring seal that can occur before it yields depends upon whether only the leading edge of the seal is bent to conform to the door profile or whether the entire seal is customized by initially shimming it to match the jamb profile.

During physical-model experiments, it was learned that even a small fire burning at a gap between a seal and jamb can heat the seal material to about 538 C (1000 F). Because of the thermal mass of the jamb and door, these components do not rise rapidly in temperature when near small fires. It was judged that localized heating by fire of any seal design/material under conditions of constraint and seal-bending stress can be detrimental to the seal.

When the physical model was cycled in temperature to mimic operational conditions, sealing between the seal and the jamb was not lost at any time. Although the temperature levels were changed, the temperature gradients remained almost constant. The gradients remained near constant because the temperature changes occurred slowly. Tests were run in which the end-closure component gradients were increased rapidly by spraying water against the equipment in a simulation of a rain storm. There was a decrease in latch loads during the water-cooling period. This decrease had to be accompanied by a change in the distribution of sealing pressure and a change in the profile of the door or jamb, or both.

Input From Task 3 (Field Data Collection)

When obtaining measurements of jamb profiles at 4-meter and 6-meter batteries having both S-shaped and fixed-edge seals, the performance of seals was observed and numerous discussions were held with operational personnel about their experiences (and improvement approaches) with the performance of the two types of seals. Information that relates to our objective of upgraded metal seals follows.

S-Shaped Seals

Members of the project team have witnessed 100 percent emission-control performance with new and well-adjusted S-shaped seals in operation against relatively straight and relatively clean existing jambs. Performance of "100 percent" means no visible emissions at any time, including the period during and just after charging of coal to the oven. "Well-adjusted" means that considerable skilled effort was expended to adjust the plunger-spring pressures acting as a point loading against the back of the seal edges. This observation relating to seal performance agrees with the analysis summary of Task 1 to the effect that the S-shaped seal is fundamentally a good approach. This observation also confirms that, in general, the metal-to-metal seal approach is sound.

However, it was observed that with time (often less than 6 months), the emission-control performance of these standard seals began to deteriorate. Deterioration of standard S-seal performance also occurs at 6-meter batteries where the jambs are mechanically cleaned, the jambs are not warped, and the seal edges have not been nicked. Reasons for this deterioration will be discussed in a later section.

Fixed-Edge Seals

Members of the project team have never witnessed 100 percent emission-control performance with fixed-edge seals. Operational personnel were asked in several instances to attempt to reach 100 percent control by adjusting the seals working aginst both well-cleaned jambs and uncleaned jambs. It is appreciated that it takes skill and experience to adjust a fixed-edge seal, because the seal itself acts as a beam so that forcing it inward at one location can result in a rocking action causing a force on the beam acting outward at another nearby location. Even with diligent and experienced effort, 100 percent emission control was never achieved. Leakage is particularly severe when attempting to adjust the fixed-edge seal in contact with a clean jamb. This is a negative observation on fixed seals, but it should be noted that there is at least one battery having fixed-edge seals that has a low percentage of leaking doors. It has been stated that, to reach a standard of less than 10 percent leaking ovens on a battery, it is necessary to lower the average leaking time per oven (both doors) below 1 hour. There is at least one fixed-edge-seal battery where the oven leaking time is rather uniform between 15 and 20 minutes, indicating about a 3 percent door-leakage rating for the battery. Our investigation at one of these "rapid-sealing batteries" indicates that (a) the jambs are only mildly bowed and (b) the door and jambs are bowed in the same direction, i.e., the door and jamb were almost congruent. It was judged that the jamb deposits in this instance helped fill gaps. The amount of leakage and the duration of leakage was always high when we asked operators to scrape the jambs to bare metal.

Task 1 results indicated that with fixed-edge seals it is not possible to obtain a transfer of the door-latching force to a well-distributed seal/jamb contact pressure. Considering that our research

(c) The most important measurement, with regard to retrofittable seals, was found not to be that of the jamb profile itself *but rather the measurement of the variation in the horizontal distance between the fastening point of the seal on the door frame and the seal-mating surface on the jamb.* This distance is discussed in the following paragraph.

Measurements were taken (from a vertical reference plane) on the end closure of a 4-year-old, 6-meter battery to obtain the relative profiles of the jamb sides and the outboard side of the flat, steel-door frame. The thickness of the cross section of the steel-door frame was constant along the length of the door and the measurements were used to calculate the variation in horizontal distance between the jamb and the line on the door where the S-shaped seal was fastened to the door. These data could be presented as profile relationships, but it is more informative to adjust the data to simulate the first contact of the seal and jamb. These adjusted data are as follows:

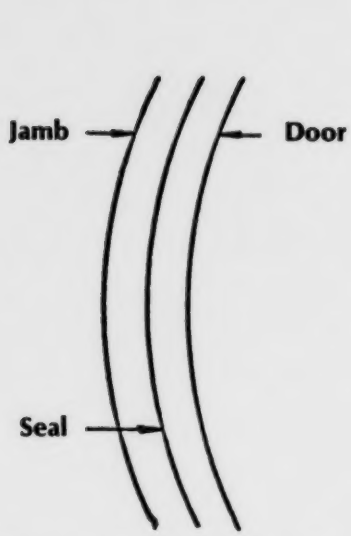
Vertical Distance from Bottom of Jamb, m	Distance Between Seal Edge and Jamb When First Contact is Made, mm	
6.6	5.1	5.7
5.7	2.0	2.8
4.8 –Latch Point	0.0	0.2
3.0	0.4	0.0
1.5	3.6	0.1
0.9 –Latch Point	3.1	0.5
0.1	5.0	3.9

1 m = 39.37 in.; 25.4 mm = 1 in.

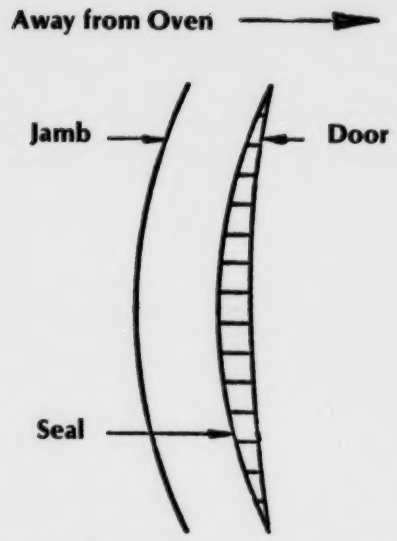
In this case, both the jamb and the door had an inward bow with the latched door having a greater inward bow (smaller radius of curvature) than the jamb by about 5 mm (about 0.2 in.). The measured curvature of the door was more pronounced above and below the latch points.

It was concluded that, unless the upper and lower edges of the seal had been pushed forward (inward) by increasing the backup spring pressure in these areas, upon latching the S-seal portion between the latches had to bend back about 5 mm (about 0.2 in.) before the seal edge made first contact with the top and bottom cross pieces.

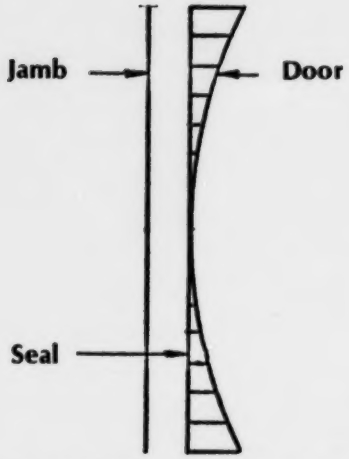
Relative to the other existing jamb and door profile relationships, the above example could be labeled a "good" congruency. There are instances in which the jamb and the door body bow towards each other. A sketch of this relationship and other variations that exist in terms of relative contours are shown in Figure II-7.



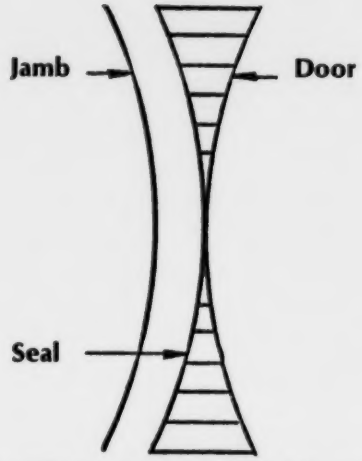
Example A. Horizontal distances between jamb and door are all the same.



Example B. Door has less curvature than jamb. Jamb corners are closer to door than at the middle of jamb/door.



Example C. Door is curved inward and is facing either a straight jamb or distance between jamb and door is greater at the corners.



Example D. Jamb and door bow towards each other.

FIGURE II-7. EXAMPLES OF VARIATIONS THAT EXIST IN TERMS OF THE RELATIVE CONTOURS OF JAMBS AND DOOR FRAMES

Damage/Changes Observed in Operating S-Shaped Seals

This section of the report deals with the observed or measured damage and dimensional changes that often take place in standard S–shaped seals.

Coke-plant superintendents often indicate that they think that their 304 stainless steel S-shaped seals are "too soft" and "damage too easily". Relative to other materials, 304 stainless steel does have these disadvantages. Many examples of nicks and bends on seals can be seen on visiting or working at coke plants. It was judged that 304 stainless steel should be replaced with a higher strength and tougher material if for no other reason than to minimize dents and bending damage. With regard to this type of physical damage, Battelle researchers did not include any effort in this project to devise methods for shielding seals from bumping damage. One approach would be the retrofitting of additional bumpers and guides. There are indications that the research organizations of steel companies have done research on this subject, and that the results may become available. *The development of suitable door guides and door stops is an important consideration in long-life seal performance.*

Another type of visible damage is caused by the spring-plunger back-up loading of the S-shaped seal. Calculations made in Task 1 indicated that, on the average, about 70 percent of the latching load is absorbed by the spring-loaded plungers pressing against the back of the seal edge. Under conditions where the seal and plungers are forced backward in a large deflection, damage to the back of the standard seal can occur as shown in Figure II-8. Shown is a photograph of a portion of a discarded S-shaped seal. Indicated are the depressions made in the back of the seal edge by the plungers and the resulting waviness of the seal edge. According to coke-plant superintendents this type of damage is not rare.

According to calculations made in Task 1, the use of point loading (as with plungers in the S-shaped seal system) does not distribute the latching force very well between the plungers. It is also indicated that, under some conditions, point loading of the back of the seal strip can result in (a) physical damage to the seal, and (b) the opening of gaps between the seal edge and the jamb.

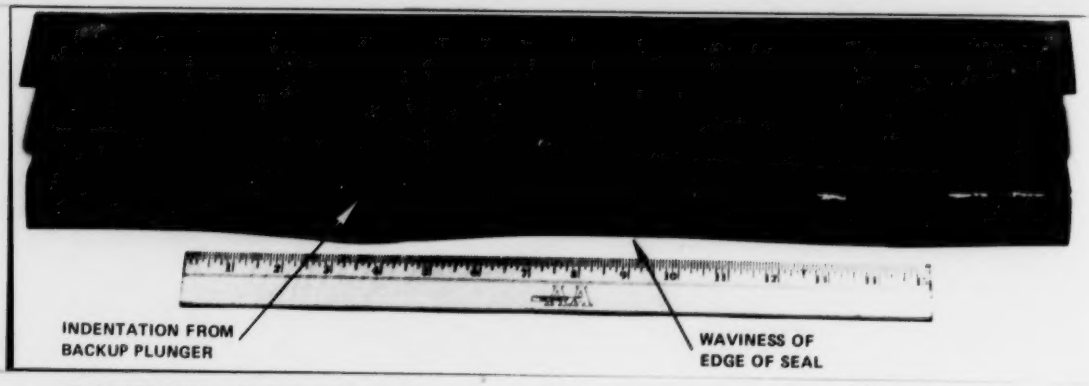


FIGURE II-8. PHOTOGRAPH OF A DISCARDED S-SHAPED SEAL SHOWING INDENTATIONS AT THE PLUNGER CONTACT POINTS AND THE RESULTING WAVINESS IN THE SEAL EDGE

Creep and Relaxation. There are indications that the S-shaped seal rather rapidly goes through dimensional changes during service. These changes occur by the action of yielding as creep and/or stress relaxation with the result that the seal edge assumes or attempts to assume the same profile as the mating jamb. U.S. Steel Research data indicate that this accommodation of the seal can take place in four coking cycles or less. This accommodation appears to be advantageous in terms of attaining congruency between seal edge and jamb profile, but gaps between the seal edge and the jamb could develop due to nonuniform plastic deformation. Battelle researchers believe that the stress level and temperature level vary along the standard S-seal. Therefore, the degree of plastic deformation could vary with the result that gaps can develop between the seal edge and the jamb.

It would be expected that the gap-forming problem caused by deformation would be more severe at coke plants where the seals are at a higher temperature than at other batteries. In general, this has been observed to be correct. It is recommended that future batteries should be designed to have significantly lower operating temperatures on all elements of the end closures. However, in terms of retrofit, one approach to be considered is the use of materials more resistant to plastic deformation.

Seal Adjustments and "Life on the Bench". To a limited degree, both the fixed-edge seal and the S-shaped seal are adjustable. As noted in the introduction to this section of the report, if a considerable amount of "tuning" of a new S-shaped seal is performed by skilled personnel, a new S-shaped seal can be made to be 100 percent emission free – for a time, and if the door-to-jamb spacing is within the limits of the adjustability of the seal. This can be done, but it is not being done, or it is not being done often. There are probably more reasons why it is not being done than we appreciate, but, based upon our experience, it is not being done mainly because there is really not enough time between equipment moves to do the job efficiently or effectively. Adjusting seals or making repairs (patching) on oven ends is somewhat akin to doing ceiling repairs in an operating subway. You have to know the schedule and estimate the time you have to work. With this information in hand, the next decision to make is whether to attempt to do the job working from the ground (the bench) or do it right and get up to the job. Given that the "work" is at the top of the jamb, the next step is to move the scaffolding equipment into place (team operation) and start climbing. Once in place, whether doing measurements or repairs, the feeling persists of "get the job done fast and get the heck down from there". This feeling exists because it is not unknown for a machine operator to "wipe out" a scaffold arrangement on the bench. In moving from working on a 4-meter battery to working on a 6-meter battery, the difference is somewhat akin to working on a step ladder as compared with working at the top of a long extension ladder. In summary, the equipment and the tools and the time are just not available for the job that has to be done. For the taller batteries of the future, we suggest that the designers first personally work for a brief period at the top of jambs and then perhaps equip the battery with powered monorail cabs for single-man repairs.

As a result of our own experiences taking measurements on jambs and doors, it was suggested to our designers that "to the degree possible, attempt to eliminate the need for above-the-bench adjustments". Based upon our discussions with coke-plant supervisors, this approach has to be demonstrated before industry acceptance is obtained.

Input From Other Sources

Prior to the start of this project, it was understood that steel companies having data on end-closure measurements and seal performance would share these data with Battelle researchers. One of the objectives of this sharing was to minimize the duplication of efforts. In the introduction to this report, special acknowledgment was given to the Research arm of the United States Steel Corporation for forwarding to Battelle a detailed report entitled "Coke Oven-Door System Technology; Field Data From Clairton Works".

Some of the data presented in this USS report were new to the project team and some of the data confirmed our own measurements. Some of the more important information extracted from this report is as follows:

1. Most of the measured gaps between S-shaped seals and the jambs were in the range of 0.4 to 0.8 mm (0.015 to 0.030 inch). For this size of gap, sealing time (filling with tar) exceeds 1 hour.
2. The temperatures of seals and their temperature profiles varied from cycle to cycle.
3. USS researchers recorded an unusual temperature excursion during the period when they were monitoring seal temperatures. With a door on an empty oven for about 3 hours, the maximum seal temperature reached about 385 C (725 F). At this point, the aspiration steam was turned on for charging. The seal temperature rapidly rose to 438 C (820 F), but began to fall rapidly as the oven was charged. In subsequent tests, this temperature excursion was not duplicated.
4. Periodic measurement of the vertical contour of the seal edge interfacing with the jamb (taken with the doors off the oven) indicated that the seal edge rather rapidly developed a permanent "set" in conformation with the jamb contour. These measurements were taken after four coking cycles. It was stated, however, that this yielding of the seal edge to assume the contour of the jamb did not necessarily, by itself, result in satisfactory sealing.

The above extracts are not direct quotes from the USS report. The information on the yielding of the S-shaped seals was particularly important to the project team.

General Requirements for Upgraded Metal-Seal Systems

This present development project is an outgrowth of a preceding project. As in the preceding project, the Sponsors specified that they wanted an analytical approach as contrasted to an empirical approach.

The original scope of work for the Concepts Project, as stated by the joint contract with EPA and AISI, specifies that the techniques and technical advances developed should meet, to the greatest extent possible, the following *functional* criteria:

(a) Capable of being retrofitted to current and contemplated slot-type coke ovens, encompassing all oven heights and construction types

(b) Compatible with existing door-handling and oven-end working machinery

(c) Operability and reliability commensurate with present coke-oven practice

(d) No creation of additional or different environmental problems

(e) No adverse effect on product quality.

During the Concepts Study, *evaluation* criteria were developed by joint efforts of EPA/AISI/BCL. In this instance each criterion was given a weighting factor to indicate a relative degree of importance. These evaluation criteria (with comments) and the weighting factors are as follows:

Criteria Listing		Weighting Factor (Scale of 1 to 10)
1. Relative Effectiveness to Lower Emissions (Stop Smoke)	(highest rating)	10
2. Low Operating and Maintenance Cost (Note that the above criteria are rated higher than initial cost or development cost)		10
3. Capability of Retrofit		9
4. Relative Life (Longer than the standard seals)		8
5. Avoids New Safety or Environmental Problems		8
6. Avoids Increasing Length of Door-Handling Cycle		7
7. Equipment Less Sensitive to Damage, Error, Abuse or Nonstandard Operating Conditions		6
8. Relative Cost Installed		6
9. Avoids Affecting Coke Quality		6
10. Availability of Expendable Materials or Components		4
11. Does It Decrease Operation Complexity and/or Minimize Operator Options?		4
12. Relative Maintainability		4
13. Cleanability		2
14. Operator Skill Requirements		2
15. Cost for Development		1

In addition to these jointly developed evaluation criteria, in the Concepts Report Battelle researchers added additional *technical* specifications in question form as follows:

1. Will it tolerate a 200 to 315 C (400 to 600 F) operating temperature?
2. Will it tolerate a temperature excursion to 427 C (800 F) for short periods without destruction?
3. Will it have increased gap-closure capability?
4. Automatic gap-closure capability? (Can the need for manual adjustments be avoided?)
5. Resistant to corrosion and chemical attack?
6. Total-failure proof?
7. Avoids new cleaning problems?

After the presentation of our recommended seal design/material, the new seal was critiqued using the above criteria as a frame of reference.

Technical Conclusions and Recommendations
(Input to the Design Task)

The summaries of Tasks 1, 2, and 3 (with reference to seals) provided the source material for the list of conclusions and recommendations. These conclusions and recommendations that lead to the preliminary designs presented later in this chapter were:

1. For maximum visible emission-control effectiveness, convert all fixed-edge and S-shaped seals to upgraded spring-type seals. Spring-type seals have inherent advantages in terms of (a) improved control of emissions during the early part of the coking cycle, (b) accommodating small changes in door and jamb profiles either during in-cycle variations, or temperature excursions causing high thermal gradients in the end-closure components. Most fixed-edge-seal end closures need the retrofit of a spring or flexible type of seal to meet performance standards. There may be some batteries with fixed-edge seals that, as they stand (or with an increased level of manual adjustments) will meet some accepted standard of performance. Where standards are being met, retrofit to spring-type seals will depend upon a costs/benefit evaluation.
2. The new spring-type seals should have no point loading of any kind. This means a shift away from spring-loaded contact points to having the seal design/material absorb all or almost all of the latching force. Stop bolts may be used to limit the maximum deflection of the seal, depending on the particular combination of seal and material recommended.
3. Develop a preferred seal-adjustment method that moves the entire seal element in or out rather than bending one part of the seal to make a closure. This will (a) help to distribute the latching force more evenly in terms of seal/jamb contact pressure and will also (b) tend to average out the stress level at various locations on a seal by minimizing the high-pressure points and "filling" in the low-pressure (or no contact) points.

4. Consider the use of high-performance, high-temperature alloys for seal construction. This selection is to be aimed at:
   a. Allowing an increased amount of seal deflection while remaining well within the material's elastic limit and avoiding creep and relaxation problems
   b. Upgrading the seal material by increasing the resistance to damage and abuse and resistance to thermal stress.

   It is expected that most high-temperature alloys will have acceptable resistance to coke-oven corrosion conditions.
5. Special consideration and design attention should be given to the stress distribution that develops on flexing the corners of seal designs.
6. Consider increasing the seal/jamb contact pressure by narrowing the contacting width of the seal edge. The concept of having a replaceable seal edge should be considered for retrofitting seals to be placed in operation against hourglassed jambs.
7. Costs and implementation speed should be considered in selecting a retrofit design. It is considered probable that the least-cost approach will be to fit a new seal into the space that is presently available.

The Recommended Design of Retrofittable Seals

During the first three tasks of this project, various design concepts and the listing of recommendations were developed concurrently. Following the final listing of desired specifications in the early stages of Task 4, various concepts were discarded until only one remained. This remaining design which became our recommendation is presented in this section.

Description of the Recommended Seal

The retrofittable seal recommended by Battelle is illustrated in Figure II–9 as it would appear as a replacement for an S-shaped seal. The seal ring is somewhat similar to that of the S-shaped seal, but is different in several features. The seal lip is 9.5 mm (3/8 inch) high instead of the approximately 25-mm (1-inch) lip on the S-shaped seal. Two bends are required to form the new seal rather than the three required for the S-shaped seal. The seal ring may be backed up by optional leaf springs.

The seal ring and flat leaf springs are secured to a mounting angle which is a standard structural shape. The mounting angle, in turn, is mounted on the door frame using studs at the same locations used for mounting the conventional S-shaped seal. A spacer (whose function will be described later) is placed between the mounting angle and the door frame.

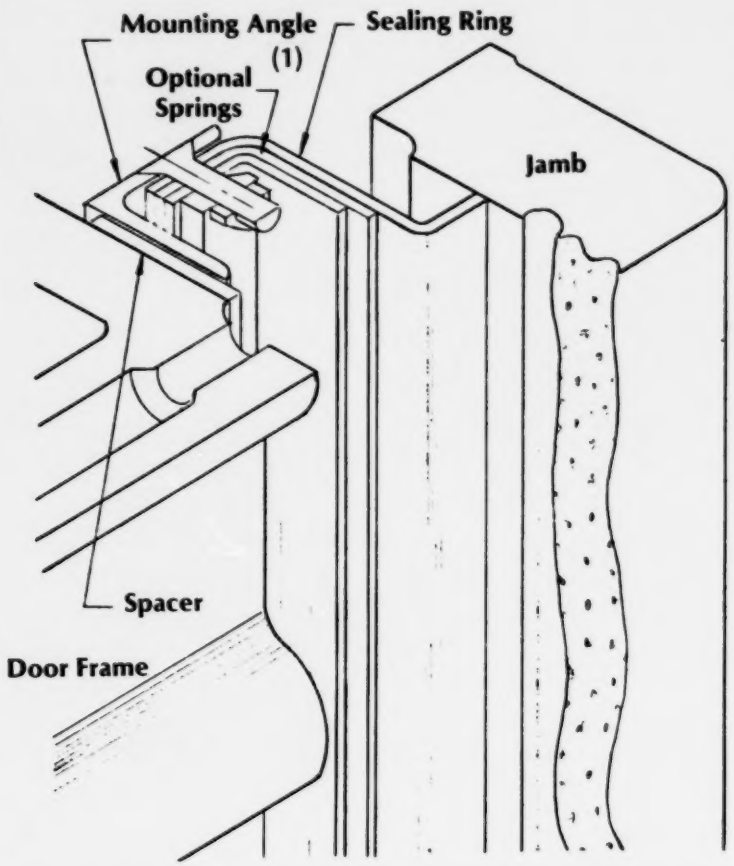


FIGURE II-9. RECOMMENDED RETROFITTABLE SEAL

No changes are made to the jamb, the door frame, or the lining, or to their spatial relationships.

This same seal with optional leaf springs may also be used as a replacement for a typical fixed-edge seal. However, the mounting method will be different and some modification of liner and liner retainers will be required.

The space available for retrofitting seals in a typical 4-meter Koppers and Wilputte battery is shown in Figures II-10 and II-11. These dimensions are based on reference drawings considered by the designers to be typical of each of the conventional systems in the 4-meter size range. Existing batteries may have dimensions different from the typical designs, because operators may request changes at the time of construction or make modifications in later years.

(1) The use of optional springs was discontinued early in the demonstration project.

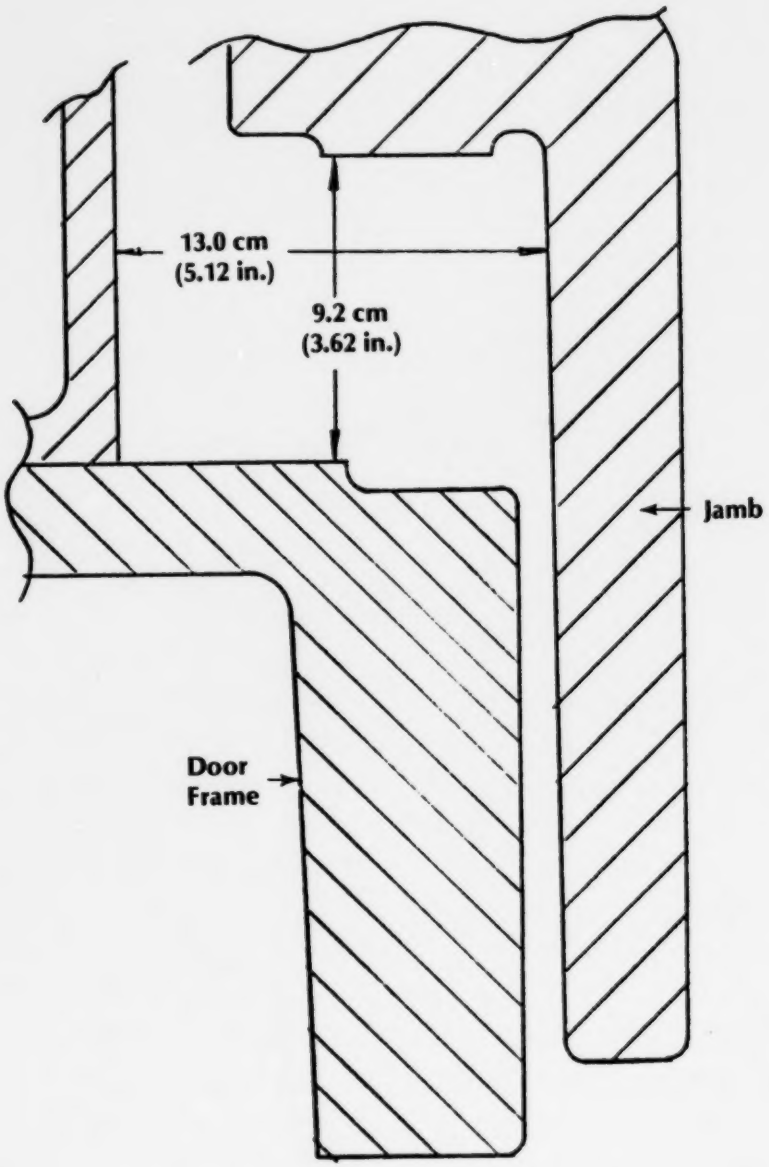


FIGURE II-10. TYPICAL KOPPERS SEAL AREA WITH SEAL REMOVED

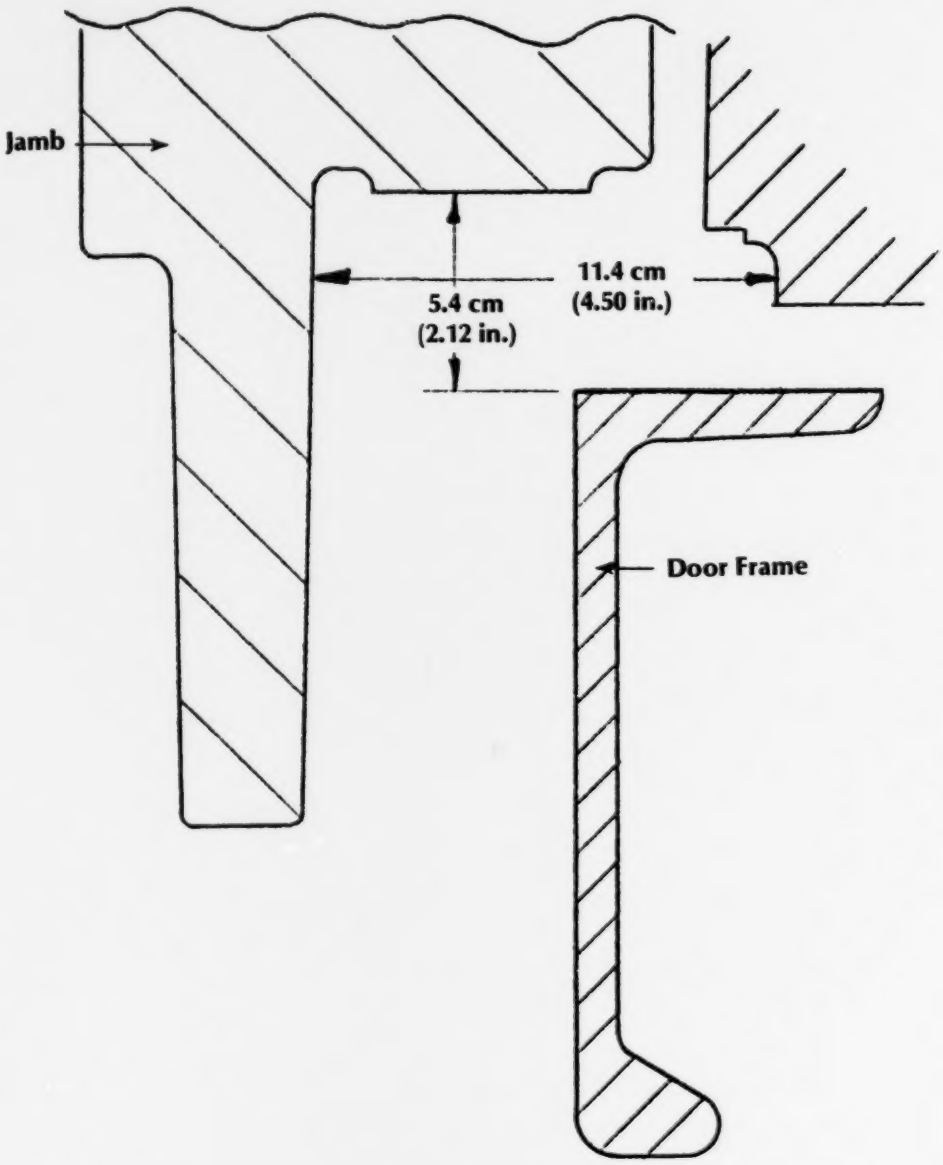


FIGURE II-11. TYPICAL WILPUTTE SEAL AREA WITH SEAL REMOVED

Material for the seal ring as shown in Figure II–9, is 2.5 mm (0.15 in.) thick. Another thickness could be selected, as appropriate. The thickness or width of the optional leaf springs is to be determined for each application. The seal lip is 9.5 mm (0.375) wide and is much more flexible along the jamb than the S–shaped seal. This increased flexibility allows the seal ring to conform more easily to a bowed jamb. Across the seal ring, which must be made of high–strength material, the seal can be deflected 7.6 mm (0.30 in.) without exceeding the elastic limit of the suggested materials.

As shown and described, the recommended seal has a greater flexibility than conventional S–shaped seals.

Several methods of installing spacers may be used. One is to use metal blocks of required thicknesses at suitable spacings. A suitable nonshrinking cement would be used to fill the gaps between blocks. Another method would use metal bars of appropriate length and thickness stacked to attain the desired space between seal mounting angle and door frame. This method, also, would require a suitable cement, but the gaps would be smaller than in the previous method.

The use of spacers requires the following steps:

- Determine the spacer requirements from measurements taken with the door in place on the jamb at operating temperature. These measurements can be obtained rapidly and accurately with simple but specialized measuring equipment.
- Take door to repair facility.
- Repair door as required.
- Install recommended seal using spacers and cement as required.
- Set corner stops to avoid overstressing the seal corners while the door is being heated during the first several cycles.*
- Place door in service.

Response of the Sponsors to the Seal Recommendations

The objectives of delivering a formal interim report, which included design recommendations, was to (a) obtain input and reactions from the sponsors and (b) to obtain permission to design and develop the seal if a consensus was achieved. The Interim Report was reviewed in detail by the Coke–Practice Committee of the American Iron and Steel Institute. This committee consists of coke plant superintendents from most of the membership steel companies.

Battelle's recommendations were accepted with reservations only in one area. The concept of taking measurements at coke–oven doors and using this information to put "spacers" under the

*U.S. Steel research data indicate that it takes two or more coking cycles before a door achieves its equilibrium thermal bow.

seal during the seal-mounting operation (to "shape" the seal edge to the needed profile) appeared awkward and undesirable to probably a majority of the coke plant superintendents.(1) It also appeared to some that this approach would "freeze" a particular door and seal combination to one oven, i.e., the seal would be a "custom fit" for only one jamb. Custom fitting would interfere with the present ability to (a) take a door from oven A16 and put on a new seal and then (b) place this door in operation at oven A32, for example.

The subjects of measurements and the use of spacers under seals were discussed at length at several meetings. The positions of the Battelle researchers were as follows:

1. The use of spacers would only be required at ovens and batteries where the end closure components were near hopelessly warped. Our concept of retrofittability was to be able to handle almost any incongruency of door and jamb profiles. At coke plants having relatively good congruency of jamb and door profiles, the increased flexibility of the seal to be designed would obviate the need for consideration of spacers.
2. In order to know whether the end closures on a particular battery are, say, a warped mess, or conversely if all components are in reasonable alignment; it would be necessary to take some measurements. Visual inspection gave some indication of the situation but (it was established) this approach was influenced by subjective considerations.
3. Measurements taken by Battelle researchers at end closures indicated that jamb warpage at a particular battery follows a general pattern. The variations in the general patterns are shown in exaggerated form in Figure II-7. The point, however, is that if there is an outward bowing of jambs at a battery, all or almost all of the jambs bow outward. Given a pattern of warpage it is only necessary to use a standardized approach to the installation of seal-shaping spacers, i.e., use the same thickness of spacers at particular locations on all doors on a side of a battery. This was one of the reasons that increased seal flexibility was a major recommendation.

It became apparent that coke plant superintendents were concerned about having the people with skills on hand to obtain the desired measurements. Continued discussions indicated that many coke plant superintendents had made serious attempts to obtain end closure measurements. Examination of these results indicated that (a) the data were completely unreliable and (b) the coke plant

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(1) A recent discussion with USSR coke-plant technologists visiting the United States and EPA would seem to indicate that a generalized form of spacer use is now standard on 7-meter batteries in the USSR. The term generalized is given to mean that the same top and bottom spacer thickness is installed between the seal and the door frame on all doors.

superintendents had reason to doubt measurement accuracy to be taken at coke-oven end closures. Keeping this in mind, the researchers resolved to pare down the methods to some very simple method. The results of this effort are included in the summary of the seal demonstration efforts.

Battelle personnel learned much during the discussions. The overall concensus drawn was that Battelle should proceed with the design/development and testing of the recommended approach for retrofittable seals.

CHAPTER III

DESIGN AND LABORATORY TESTING OF THE ACCEPTED SEAL CONCEPT

Following the acceptance of the design concept of the upgraded metal-to-metal seal, by the sponsors, the next tasks were to:

- Evaluate full-scale portions of the recommended seal in laboratory testing equipment to (a) determine whether the pre-engineering expectations could be confirmed prior to placing orders for demonstration seals and (b) develop data for use in the design effort
- Provide the engineering drawings for the fabrication of the recommended seals for retrofit to both Koppers and Wilputte designed doors.

Summary of High Temperature and High Stress Testing of Candidate Materials for Coke-Oven Door Seals

One of the first subtasks was to evaluate the candidate alloys (with high tensile strengths and resistance to heat) to be used to increase cross-sectional flexibility of future seals by a factor of 2 to 3 over existing seal materials.

The Interim Report stated that the first choice of a possible alloy for upgraded seals (for testing) is Inconel X-750. This alloy is manufactured by Huntington Alloys and it is a nickel-based, precipitation-hardening (during heat treatment) alloy normally chosen for long-term service for springs operating over 315 C (600 F). In the annealed or as-received state, this alloy is readily formable into parts and at the time of the preparation of the Interim Report, this alloy was readily available in sheet and strip form. (This availability disappeared later in the project as a result of increased aerospace activity—just when the alloy was needed for demonstration seals). However, the Interim Report also stated that the laboratory testing of Inconel X-750 should be followed by testing of various types of precipitation-hardening stainless steels, i.e., iron-based alloys in this instance. For example, Armco Steel personnel recommended the testing of 17-4 PH stainless steel provided that a fabricator could "handle" the relatively difficult formability of this particular alloy. To avoid complicating our dealings with potential fabricators of demonstration seals, a decision was made to evaluate only those high-strength alloys known to be relatively easy to form into shapes.

A survey of the precipitation-hardening stainless steels indicated that both Custom 455 and PH 15-7 Mo could be of interest. A comparison of Inconel X-750 and the two stainless steels is given in Table III-1. This table lists some of the important mechanical characteristics of the materials (to the degree that they are known) and our comments in terms of various attractive and possibly detrimental or expensive-to-fabricate characteristics.

TABLE III-1. COMPARATIVE INFORMATION AND JUDGMENTS ON THREE CANDIDATE ALLOYS FOR MANUFACTURE OF COKE-OVEN SEALS[a]

Material	0.2% Offset Yield Strength at 800 F, ksi	Producer's Recommended Upper Temperature Limit for Spring Applications, F	Basic Price/Availability per Pound (for Demo Project), $/lb		Stress to Rupture in 1000 Hr, ksi[c] 600 F	Stress to Rupture in 1000 Hr, ksi[c] 800 F
Inconel X-750 (Aged at 1300 F)	140[b]	900	5.00	Available now	180	130
Custom 455 (Aged at 1000 F)	150	600	2.60	May be able to obtain a rush order from the mill	160	80
PH 15-7 Mo (Aged at 1050 F)	150	600	1.60	Minimum 2000 lb mill order	170	150

Material	Stability Comments	Desirable Characteristics	Undesirable Characteristics from Viewpoint of this Application
Inconel X-750	Stable to 1000 F	1. Superior alloy for low creep and relaxation at temperatures above coke-door temperatures 2. Sheet and strip available	1. Welds require fast, 1800 F heat treatment 2. Aging step is more than 20 hours long
Custom 455	Precipitation continues for temperatures over 600 F. Alloy can become brittle	1. Simple, 4-hour heat treatment at 950 to 1000 F 2. No weld annealing required	1. Low stability temperature. Alloy can overage at temperatures of 600 F
PH 15-7 Mo	Same as above, but at a slower overaging rate	1. Lowest cost 2. No weld annealing required	1. Alloy can slowly overage above 600 F 2. Producer expects warping during heat treatment. Suggest retaining rig used during heat treatment

(a) There are many precipitation-hardening steels and superalloys; additional alloys are being developed. The alloys given below have the desired thermal expansion coefficients and are available (some only after a wait to complete a mill order) in sheet or strip form.

(b) The actual stress levels fall within a range and can be different from lot to lot of product. A finite number is included in this table because in some cases the data are presented in this form in the literature.

(c) The stress-to-rupture data included in this table may not be indicative of the expected performance of these materials in a coke-oven seal application. However, it is "usual" to present these data for some comparative information. These data are presented here because creep and relaxation data are either not available or are not considered (by us) to be particularly useful when the desired testing temperature (800 F) is in the range where the alloy is not metallurgically stable. Laboratory testing is required.

NOTE: Degree Centigrade = Degree Fahrenheit - 32/1.8; 1 ksi = 6.9 MPa.

Our Approach

In the metallurgical and mechanics fields, many definitions are somewhat controversial, including the definitions for creep and relaxation. For the spring seals for coke-oven doors, we will use the oversimplified definition that creep is the time-related permanent bending (distortion) of the seal occurring under constant load. Relaxation will be defined as the time-related decrease of the load-carrying ability of the seal under constant deflection. Although creep and relaxation characteristics are prime considerations in selecting a seal material, we recommend the continued use of corner stop bolts to further reduce the possibility of long-term degradation and the possibility of short-term overstressing of the seal components.* The use and adjustment of the stop bolts allow a means (more or less) of distributing the entire latch loading between the recommended seal and the stop bolts. We feel that this is required because (a) we are dealing with a retrofit situation and (b) we do not know what range of latch loading will be encountered at coke plants. It would be our judgment that the latch loadings will almost always be lower than the design or start-up operation loading. With the probability of nonuniform latch loading to consider, we elected (a) not to try to make one seal design absorb the entire latch loading and (b) to try to design the seal (by "setting" the length of the single support leaf below the main seal leaf) to reach a near maximum deflection with a latch load of about 75 percent of the design loading. Any loading above this minimum would be transferred to the jamb via the stop bolts. We regard this approach as an accommodation to expected latch-force realities and have hopes (to be checked out in the demonstration project) that, by this approach, special efforts to bring latch loading "up to design" can be avoided in most instances. We appreciate that some designers may consider it important that the upstanding edge of the metal seal be pressed against the jamb (and jamb deposits) with some force. Our position is that (a) it is critical that the seal touch the jamb all the way around the door, (b) the jamb/seal contact pressure may only have a small bearing on controlling emissions, and (c) it may be an important consideration that a large deflection of the recommended seal will "rock" the contacting seal edge over to its inside edge during latching. This represents concentrated and near knife-edge pressure that may or may not be helpful in cutting into jamb deposits.

In using the stop bolts the amount of seal deflection may be controlled between 0 and 13 mm (0.0 and 0.5 in.)—at least at the corners. With a controlled deflection of 8 mm (0.3 in.), distortion by creep should not be a problem unless the seal is inadvertently overdeflected at some location. In an effort to prevent this possibility we elected to use the "spacing approach" in order to get the seal and jamb congruent at the start of a campaign. With implementation of this approach it is expected that seal deflection will be "set" via the stop bolts and any time-related variations between the congruency of the jamb and seal/door will be absorbed by the flexibility of the seal.

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*For Wilputte doors we recommend the installation of stop bolts when the recommended seal is installed.

Test Samples and Test Equipment

Requests for strip samples were sent to the various producers of the candidate alloys. Each producer was asked for annealed strips as close as possible to 2.5 mm (0.10 in.) in thickness. The alloys received and the thickness of the samples were as follows:

Alloy Designation	Thickness
Inconel X-750	2.39 mm (0.094 in.)
Custom 455	2.08 mm (0.082 in.)
PH 15-7 Mo	2.46 mm (0.097 in.)

To produce the test specimens, 25.4-mm (1-in.)-wide-strips of the various alloys were bent into the exact cross section of the recommended seal design. The specimens were dimensionally measured and then given the heat treatment recommended by the alloy producers.

The apparatus used for load and temperature testing consisted of a temperature-controlled oven, a vertical ram to apply a dead load on the upstanding edge of the seal specimens, a removable support fixture for the specimen, and control and recording devices.

Figure III-1 shows a specimen seal mounted in the fixture with a load applied by means of the ram passing through an opening in the top of the oven. Deflection of the loaded specimen can be seen in that figure. The lower end of the ram is recessed to guide the specimen to the center of the ram in order to centralize the load. The removable fixture permits the specimen to be moved into position. It also serves as a reference surface to measure the specimen in its initial shape, its deflection under load and temperature, its change in deflection over time (via periodic height measurements while the specimen is in the oven), and its deflection after the load has been removed. We would have preferred to work with equipment giving a continuous recording of deflection, but this equipment was not available during this portion of the project.

In the background of Figure III-1 the heating coils can be seen. The fan used to circulate the heated air is positioned behind these coils. A thermocouple was attached to each specimen to record the specimen's temperature. The leads for a thermocouple are seen in Figure III-1 going off to the right.

Test Procedures

With a specimen seal mounted in the fixture and positioned in the oven at room temperature, the spring rate of the specimen was determined by loading the seal and measuring the deflection. In order to obtain the required scale-up factors, this spring rate was compared with load/deflection measurements on a 1.4-meter (54-in.)-long specimen seal of the same material and thickness.

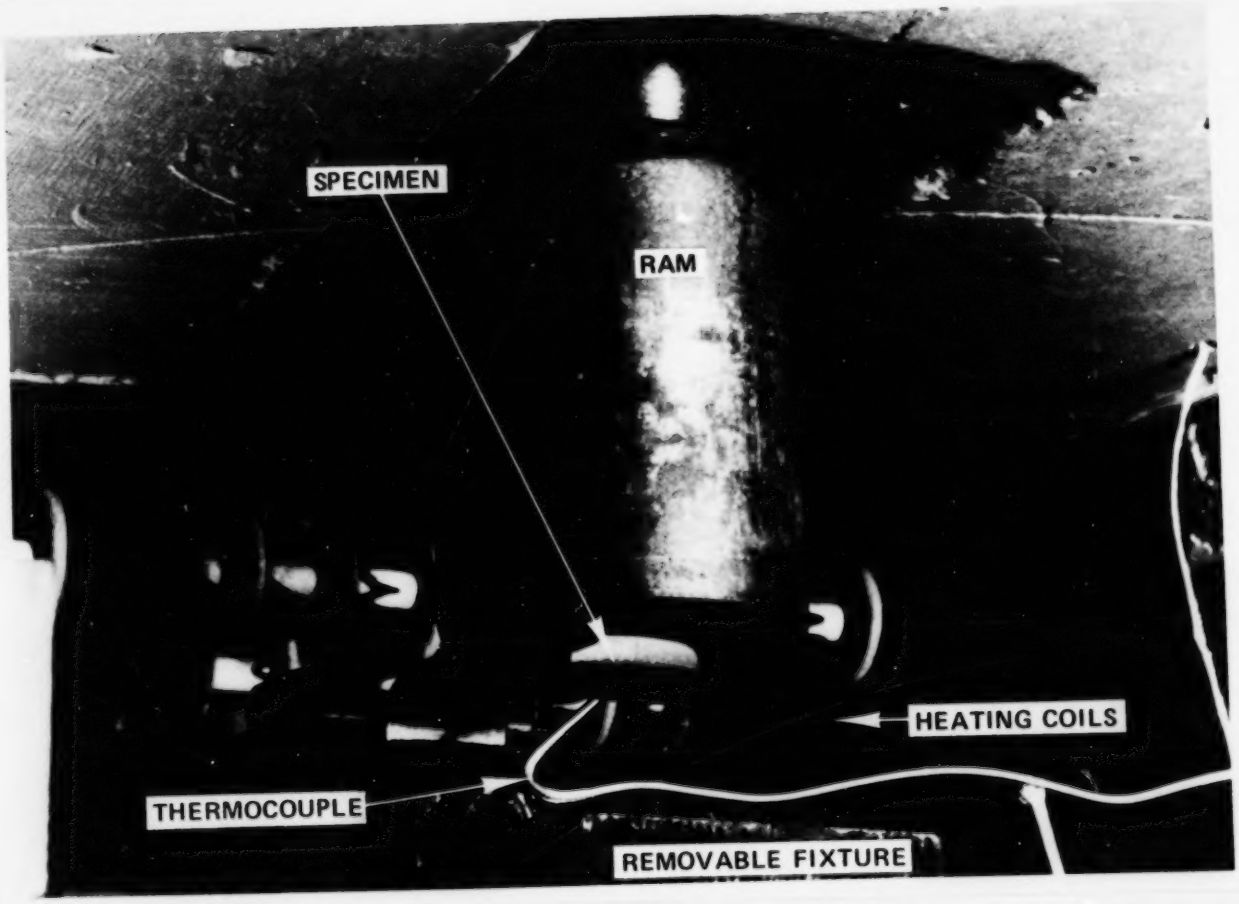

FIGURE III-1. LOADED SPECIMEN IN FURNACE

Then with no load on the 25-mm (1-in.)-wide specimen, the oven was heated to the selected operating temperature. The spring rate was again determined as a verification of (a) the change in the modulus of elasticity (Young's) with the temperature increase and (b) the stability of the mounting arrangement. As expected, there is a small increase in deflection (at constant load) upon heating the specimen.

At the selected operating temperature the load on the seal was increased in increments until periodic deflection measurements indicated that measurable secondary creep (sagging, in this instance) was in progress. The specimen and fixture were then cooled to room temperature in order to measure the overall permanent shape change and the location on the specimen where the creep effects (bending) have occurred. Approximately the same procedure was used to test specimens having a second or backup leaf spring mounted behind the main seal element.

Room-Temperature Spring-Rate Data Obtained on 25-mm (1-in.)-Wide Samples

The various alloy strips were formed into the cross section of the recommended seal. Measurements taken before and after heat treatment indicated no distortion resulting from the aging treatment. One measurement method used was to trace the outline of the untreated spring on paper for comparison with spring seal after heat treatment. Figures III-2 and III-3 are (a) an example of a sample tracing and (b) the seal as it would be positioned on a coke-oven door. These drawings indicate the cross section and true size of the spring seal.

Table III-2 presents some of the data obtained during room-temperature deflection/loading of single leafs of the 25-mm (1-in.)-wide specimens.

TABLE III-2. DATA OBTAINED DURING ROOM-TEMPERATURE TESTING OF 25-MM (1-IN.)-WIDE SEAL SAMPLES

Alloy Type	Strip Thickness		Load on End of Spring		Spring Deflection		Spring Constant Force-Deflection Rate	
	mm	(in.)	kg	(lb)	mm	(in.)	kg/mm	(lb/in.)
304 Stainless (Annealed)	3.0	(0.118)	16.8	(37)	4.3	(0.168)	3.9	(220)
Custom 455 (Aged)	2.1	(0.082)	13.6	(30)	9.8	(0.385)	1.4	(78)
PH 15-7 Mo (Aged)	2.5	(0.097)	13.6	(30)	5.8	(0.230)	2.3	(130)
Inconel X-750 (Aged)	2.4	(0.094)	29.5	(65)	12.75	(0.502)	2.3	(129)

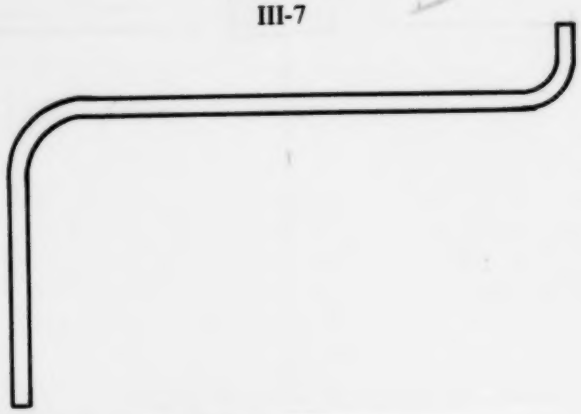

FIGURE III-2. A TRACING OF THE CROSS-SECTIONAL OUTLINE OF THE SPRING SEAL SHOWING THICKNESS AND SHAPE

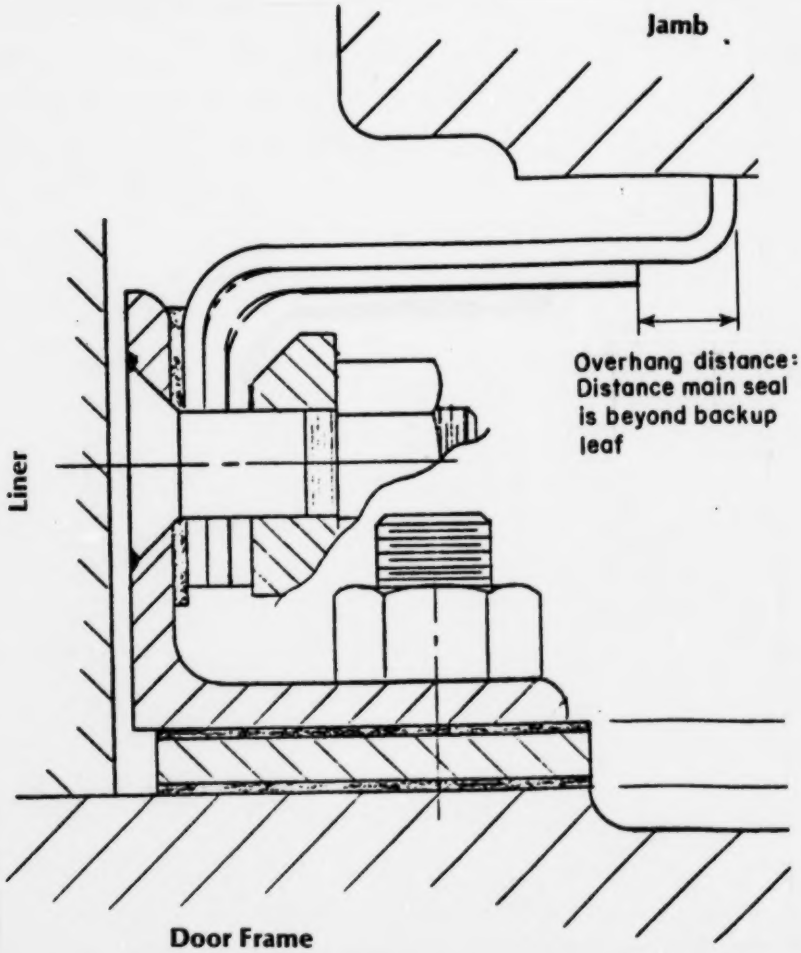

FIGURE III-3. AN ILLUSTRATION OF THE SEAL AS IT WOULD BE POSITIONED ON A COKE-OVEN DOOR. ALSO SHOWN IS THE "OVERHANG DISTANCE"

Various approaches were used in an attempt to calculate the spring rate (force-deflection rate) of what is essentially a curved-end cantilever spring. The design equations of Blake[1] and Palm/Thomas[2] for curved springs were found to be unsatisfactory, indicating only that spring design is not as yet an exact technology. Taking the approach that the curved-end spring might be treated mathematically as a straight cantilever spring, it was assumed that the measured spring rate is equal to:

$$\frac{\text{the modulus of elasticity x width x (thickness)}^3}{4 \text{ x (spring length)}^3} \quad (3)$$

Solving the spring length (given the measured spring rate and thickness, and using handbook data for the modulus) indicates that the deflection/loading characteristics of the samples listed in Table III-2 are equivalent to that of a 3.7-in.-cantilever spring.

It was appreciated that the spring rate of the recommended seal could be modified by changing the radius of the main bend. This bend is positioned close to the point where the seal is fastened to its mounting angle. Instead of exploring this possibility, the decision was made to standardize by employing a 9.5-mm (3/8-in.) radius in the main bend for both the main seal leaf *and* the backup or support leaf. It was expected that the spring rate could be more widely varied by changing the length of the backup leaf rather than by modifying the radii of the bends.

A comparison of the spring rate of the 25-mm (1 in.) samples and the spring rate of the 1.4 m (52 in.) specimens of the same material, design, and thickness indicated that the full-length seal will be about 15 percent stiffer (higher spring rate) per inch than that of the 25-mm (1-in.)-wide specimens. This is in approximate agreement with generalized spring formulas.[4] On the other hand, when heated to 315 C (600 F) there is a decrease in stiffness (lower spring rate) of about 10 percent which is partially compensating.

Table III-3 presents some of the data obtained in room-temperature testing in which various lengths of a single backup or support leaf were mounted below the main leaf. In this table the term "length of overhang" is used. The meaning of this term can be best understood by examination of Figure III-3.

The data in Table III-3 indicate that the spring constant of a two-piece spring or seal assembly can be varied significantly by changing the length of the backup leaf and thereby changing the amount of overhang.

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(1) Blake, Alexander, "Curved-End Cantilever", Machine Design, p 151, July 1959.
(2) Palm, J. and Klaus, T., "Design Equations for Curved Springs", Product Engineering, p 286, September 1969.
(3) Maier, K., "For Spring Action, Which Cantilever Beam is Best?", *Spring Design and Application,* McGraw-Hill, 1961.
(4) Wahl, A. M., *Mechanical Springs,* McGraw-Hill, 1967.

TABLE III-3. DATA OBTAINED DURING ROOM-TEMPERATURE TESTING OF 2.5-MM (1-IN.)-WIDE INCONEL X-750 SEAL AND BACKUP LEAF ASSEMBLIES

Length of "Overhang"		Load on End of Seal		Seal Deflection		Spring Constant for the Assembly	
mm	(in.)	kg	(lb)	mm	(in.)	kg/mm	(lb/in.)
0.0		36.3	(80)	6.8	(0.27)	5.3	(296)
12.7	(0.5)	36.3	(80)	7.6	(0.30)	4.8	(267)
25.4	(1.0)	36.3	(80)	8.4	(0.33)	4.3	(242)
31.7	(1.25)	36.3	(80)	9.1	(0.36)	4.0	(222)
31.7	(1.25)	45.3	(100)	11.4	(0.45)	4.0	(222)

Note: The thickness for both main seal and backup leaf was 2.39 mm (0.094 in.) and the radius of bend (near support bolting) was 9.5 mm (3/8 in.) for both pieces.

The objectives of using a backup leaf in the recommended design are to:

(a) Lower the stress concentration in the main bend in the seal (located near where the seal is bolted to its support frame), i.e., attempt to move toward a spring seal assembly having more uniform strength.

(b) Introduce a means of varying the spring rate of the assembly by changing the length of the support leaf. The support leaf does not go around the corner of the doors and consists of four replaceable pieces per door rather than one continuous leaf.

(c) Introduce an element of controllable performance flexibility in preparation for any unknowns or problems to be encountered in the demonstration project.

Given the above objectives, we should hasten to add that:

(a) It may not be necessary to use a backup leaf with Inconel X-750. This will be determined during the demonstration project. It may develop that satisfactory sealing can be attained by limiting the seal deflection (via the stop bolts) and lowering the contact pressure between the contact edge of the seal and the jamb. A backup leaf may be required when other alloys are used.

(b) With the main bend in both the seal and the backup leaf having the same radius (for simplification of manufacture), there is a gap between the two elements at the main bends; thus, the seal assembly is not a true nested-together leaf-spring assembly. Nesting the support leaf bend against the main seal bend would improve the distribution of stresses along the main seal but for simplicity of fabrication the decision was made to begin with the bends having the same radius. Because this design does not "fit" pure leaf-spring analyses, it was necessary to evaluate this arrangement empirically.

Elevated Temperature Data Collected on Single Seal and Seal Assembly (with Backup Leaf) Samples

At one time it had been planned to obtain elevated temperature creep and relaxation data on samples of any recommended seal design. Of necessity (time and funding considerations and shortage of equipment), this approach was changed and the decision was made to determine the approximate loading level where the creep rate became measurable over a 12- to 24-hour period. The information of interest was the load (and temperature) at which the sample seal (1 in. wide) began to sag.

The position has been taken that there is at least a qualitative relationship between creep and relaxation. Qualitative information about one type of behavior can be obtained from the measurement of the other.(1)

In addition, a conservative position was taken that some of the "hot testing" should be completed at temperatures higher than those expected in day-to-day coke plant operation. A top temperature of 427 C was selected based on this consideration.

While there is considerable creep information on various alloys available in the literature, there is a problem in getting information at the same temperature and condition of the material. For example, the data available on the creep and relaxation rate of Inconel X-750 deals with cold-reduced material (15 to 65 percent) processed to give the best high-temperature performance. Our recommendation was to begin fabrication with solution annealed or relatively soft X-750. It was necessary, therefore, to undertake laboratory testing rather than to depend upon published data.

Test Data. Table III-4 is a presentation of the most pertinent data obtained during the hot-test period. The conclusions drawn from these data are presented below.

Conclusions

(1) Of the materials tested Inconel X-750 has the best properties and thus is the alloy chosen to *begin* the demonstration project. Stress is directly proportional to load and inversely proportional to spring thickness (where the width and length are the same). Our test results indicated that at 427 C the Inconel specimen withstood about a 33 percent higher stress level than that of the PH 15-7 Mo before measurable creep developed. Other factors favoring Inconel X-750 are:

(a) It is a stable material at 427 C (800 F) and higher – it should not be "destroyed" in the event of door fires at the seal.

(1) Conway, J. B. et al., "Fatigue, Tensile and Relaxation Behavior of Stainless Steels", Technical Information Center, Office of Information Services, U.S. Atomic Energy Commission, 1975.

TABLE III-4. SUMMARY OF DATA OBTAINED DURING LOADING OF HEATED SINGLE SEAL AND SEAL ASSEMBLIES (1-INCH-WIDE SAMPLES)

Alloy Name	Seal Thickness, in.	Temperature/Loading/Seal Deflection Where Plastic Deformation (Sagging) of the Specimen Was Measurable Over a 24-Hour Period			Comments
		Temperature, F	Load on Seal Edge, lb	Seal Deflection, in.	
Single Leaf Seal					
304 Stainless (Annealed)	0.118	800	50	–	First test. Sample severely overloaded. 304 was found to creep at room temperature under a load of only 47 lb and with an initial deflection of 0.23 in.
Custom 455 (Aged)	0.082	600	60	–	No creep at 600 F. Yielding at 800 F and a 42-lb loading. All distortion concentrated in the main seal bend.
		700	42	0.61	
		800	42	–	
PH 15-7 Mo (Aged)	0.097	800(a)	60	0.52	
Inconel X-750 (Aged)	0.094	800	75	0.654	
Main Seal Plus Backup (1.1 In. Overhang)					
Inconel X-750 (Aged)	0.094	800	120	0.55	Length of overhang determines whether distortion will occur in the "overhang" or the bend. The particular length of overhang used was selected to distribute the distortion between the seal bend and the overhang portion of the main seal.

(a) PH 15-7 Mo is not considered structurally stable at 800 F. Given enough time at this temperature it may become embrittled.

1 inch = 25.4 mm
1 pound = 0.45 kg
°C = (°F - 32)/1.8

(b) 2.4-mm (0.094-in.)-thick sheet can be purchased in small quantities from stock.(1)

(2) If PH 15-7 Mo strip can be made available, it should be field tested during the demonstration project. At a maximum temperature of 371 C (700 F), the embrittlement rate may be slowed to the point where it may be immaterial to the life of the seal. In addition, at 371 C (700 F) the resistance to creep is increased by about 25 percent over that of an operation at 427 C (800 F).(2) Some metallurgists employed by the producers of this alloy are concerned that the alloy will warp severely during a required cooling step in the heat treatment procedure. There are indications that this may not be factually correct with this seal configuration.

(3) If it is assumed that the data present in Table III-4 are indicative of the spring rate and stress limitations to be expected in full-scale seals, then:

(a) A single X-750 seal (no backup leaf) can be deflected about 10 mm (0.4 in.) with a seal loading of about 0.9 kg/mm (50 lb per linear inch) of seal. This loading would introduce a stress level in the seal of about 60 percent of the stress reached in the creep-evident stress level recorded in Table III-4. This deflection restriction via stop-bolt settings (to 10 mm and lower) should avoid long-term distortion of the seal particularly if the time at 427 C (800 F) is very limited at the coke-oven doors. Latch forces higher than that required to produce a 10 mm (0.4 in.) deflection would be transferred to the jamb via the stop bolts.

(b) An X-750 seal with an X-750 backup leaf, under the same assumptions, could be deflected about 9 mm (0.35 in.) with a seal loading of about 1.3 kg/mm (75 lb per linear inch).

(c) In terms of seal/jamb contact pressure, a 34 kg seal load on a 25.4-mm (1-in.)-long, 2.4-mm (0.094-in.) edge is equivalent in contact pressure to 45.3 kg (100 lb) on a 25.4-mm (1-in.)-long, 3.2-mm (1/8-in.) strip. However, with the comparatively large 9 mm (0.35 in.) deflection, the upstanding portion of the seal very definitely "rocks" onto the inside edge of the seal edge and develops some "knife-edge" pressure. It remains to be seen whether this effect will or will not be an advantage in terms of cutting into carbon deposits on the jamb.

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(1) Long sheets for 6-meter doors are a special order.

(2) Perkner, D. et al., *Handbook of Stainless Steels,* McGraw-Hill, 1977.

Evaluation of Seal Flexibility

One important capability of the recommended seal is that it permits flexibility in two modes. The first mode is the cross-sectional flexibility or deflection capability in which the seal acts as a leaf spring. The second mode is the ability of the sealing edge to flex along its length in order to accommodate jamb and seal edge irregularities and to negotiate corners. The design of one mode is largely independent of that of the other, but their functions are interdependent.

The cross-sectional ability to flex and return to initial shape was determined in the temperature/loading evaluations previously described.

Evaluation of Straight Seal Sections

Advisable practice requires the recommended seal to be deliberately bowed into the same irregular profile as the corresponding jamb. The effect of this bowing on the deflection capability of the seal was evaluated with straight-section specimens at room temperature.

A universal testing machine was selected to evaluate straight sections of the recommended seal. Room-temperature evaluations appeared to be appropriate because of the specified small reduction in yield point for Inconel X-750 when heating the seal to operating temperatures. At room temperature the yield strength is 910 MPa (132 ksi). At 427 C (800 F) it is 848 MPa (123 ksi). A nominal length of 1.2 m (4 ft) was the selected specimen size. Figure III-4 shows a seal specimen mounted in place in the testing machine. H-beams were selected to provide a rigid base for the seal specimen and simulated jamb. The seal specimen was mounted on an angle in the same manner as the actual seal will be mounted in the recommended design. Spacers inserted at intervals between the angle and the beam provide any overall bow shape of the seal specimen desired. In a similar manner, the upper beam supported a flat piece of steel stock simulating a jamb-sealing surface. It, likewise, through use of spacers, could be mounted in any desired bow.

In the field-studies task of this project, the largest measured bow along the vertical sides of operating jambs was a 12.7-mm (1/2-in.) inward bow extending over a span of 4.3 m (14 ft.). This bow, of course, was an irregular contour and not a true circular arc. In the laboratory work, the bows were assumed to be circular arcs that could be duplicated in the 1.2-m (4-ft) specimen seals. These bows could be increased in equivalent 2.5-mm (1/10-in.) increments, from 12.7 mm (1/2 in.) to 25.4 mm (1 in.). Had the results indicated the need for further evaluations, the bow could have been increased beyond the equivalent of 25.4 mm in 4.3 m (1 in. in 14 ft.). Likewise, the simulated jamb surface could be bowed in the same manner so that the seal edge and the jamb surface constituted conjugate surfaces.

III-14

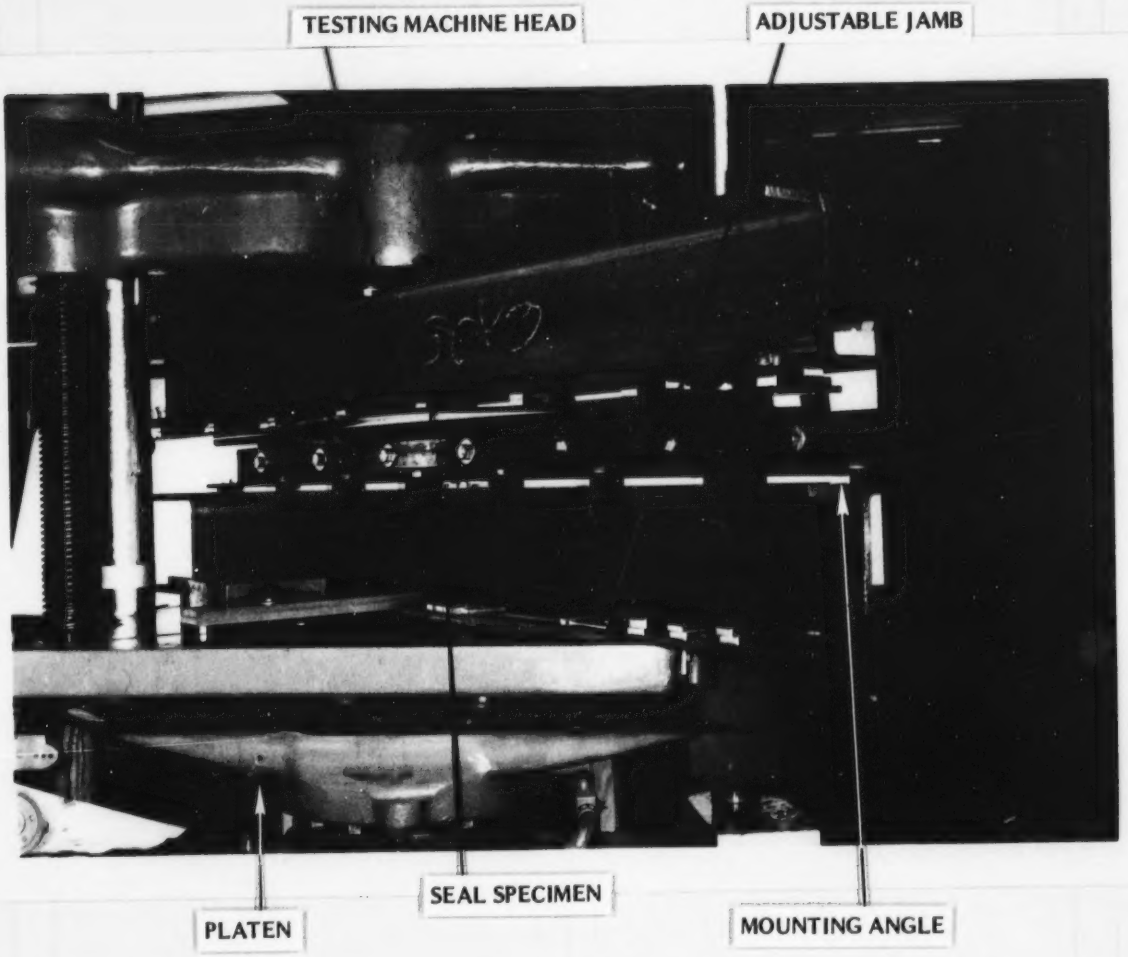


FIGURE III-4. STRAIGHT SPECIMEN OF PROPOSED SEAL MOUNTED IN EVALUATION FIXTURES

The first evaluation examined the seal specimen and the simulated jamb surface mounted in the flat (straight-line) condition. Neither had an induced bow. A straight edge was then placed on the seal edge, and gaps were measured at intervals of 100 mm (4 in.) to detect deviations from the straight-line condition. Figure III-5 is a diagram of the measured gaps. The plot shows a 0.7-mm (0.03-in.) deviation downward in the central zone of the mounted 1.3-m (52-in.) specimen seal. A smaller deviation is shown in the end area, seen in reference points 11, 12, and 13.

The testing machine was used to move the jamb surface down for initial contact with the seal edge. The amount of space between the seal edge and jamb was determined using thickness gages positioned at various check points. Next, the jamb was closed upon the seal, deflecting it 2.5 mm (1/10 in.), whereupon checks were made for any remaining spaces between the seal edge and the jamb. The jamb was removed from the specimen and the seal edge was checked to determine if it had returned to its original edge condition. Figure III-6 shows the end of a deflected specimen seal.

With the seal edge and jamb surface still in the straight-line condition, deflection of the seal was increased in 2.5-mm (1/10-in.) increments, followed by release. Checks were made for remaining gaps at each incremental deflection. The seal edge was also checked after each deflection. The seal edge was also checked after each deflection for signs of failure to return to its original free condition. These steps were repeated until a full 12.7-mm (1/2-in.) deflection was attained. The seal returned to its original condition each time with no evidence of yielding during this short-time ambient-temperature test.

Table III-5 shows the deflection conditions that were required to close the central deviation area. It was indicated that a 2.5-mm (0.1-in.) deflection of the seal closed the large irregularity to 0.025-mm (0.001-in.) gaps or less and that with a 5-mm (0.2-in.) deflection the interface between the seal edge and the mating surface was "light tight". This result was interpreted as indicating increased flexibility of the seal edge along its length.

The specimen seal and simulated jamb were remounted with an equivalent bow of 12.75 mm in 4.3 m (1/2 in. in 14 ft). Deflections and measurements were made in the same manner as before, and no creep was detected in the specimen seal.

This procedure was repeated with the bow of the seal and jamb being increased in 2.5-mm (1/10-in.) increments until an equivalent bow of 25 mm in 4.3 m (1 in. in 14 ft) was achieved and the seal was deflected 12.7 mm (1/2 in.).

Measurements were made to determine the contour of the seal edge each time the seal was mounted in a different arc. The method was the same as that used when the seal was mounted in the flat position. The edge contour was determined again after the deflection evaluations had been completed. No significant differences between onset and completion contours were apparent.

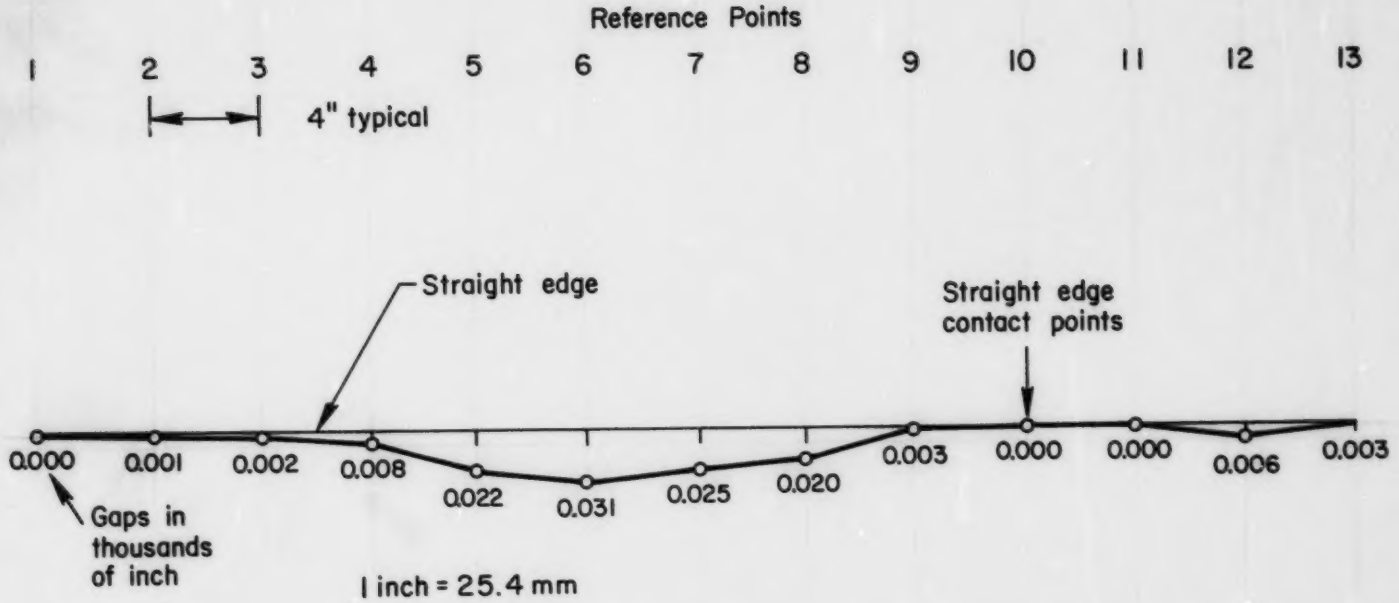


FIGURE III-5. DEVIATION OF MOUNTED SPECIMEN SEAL EDGE FROM A STRAIGHT LINE

#1312

FIGURE III-6. STRAIGHT SPECIMEN OF PROPOSED SEAL DEFLECTED IN TESTING MACHINE

TABLE III-5. DEFLECTION REQUIRED TO CLOSE GAPS

Equivalent Bow in 14 Feet, in.	Deflection, in.	Reference Points 1	2	3	4	5	6	7	8	9	10	11	12	13
Straight	0.10		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	0.20	Closed												

Note: 1 inch = 25.4 mm.
1 foot = 0.305 m.

↑ 1 foot = 0.305 m.

The testing machine loads required to deflect the specimen seal in each condition of bow are consistent for each increment of bow as shown in Table III-6. A plot of the load/deflection relationship for the most extreme condition evaluated is shown in Figure III-7.

Evaluations of the straight-line specimen seal described above had not demonstrated evidence of damage to the seal. For this reason a severe test was set up to further evaluate the seal. The simulated *jamb* was formed into a large bow having a short span and the seal was mounted in a bow of 25 mm in 4.3 m (1 in. in 14 ft), as shown in Figures III-8 and III-9. As indicated in Figure III-9, a 12.7-mm (1/2-in.) deflection of the seal almost closed a 14.5-mm (0.57-in.) gap between the seal edge and the jamb. No evidence of damage to the seal was detected, and these evaluations were terminated.

Corner Evaluation

In preparation for mechanical testing of seal corners, two fabricators were asked to produce corners (a) made of Inconel X-750 and (b) similar in design to the S-shaped seal corner. Like the S-shaped seal design, the corners had a 90 degree interior angle and a radiused outer edge or lip. The major departure from the standard S-shaped seal was the shorter lip height 9.5 mm (3/8 in.) as compared to 19 mm (3/4 in.) to increase the flexibility of the edge.

To simulate the sealing surfaces at the corner, fixtures were made of steel plate, to which a corner specimen could be mounted. The purpose was to study the deflection characteristics and to understand more about the geometric characteristics of the sealing-ring corner.

The specimens obtained from the fabricators were poorly made, having irregularities that could not be worked out by means of grinding, machining, or mounting. For this reason, the as-received corners could be used only as a means of establishing preliminary deflection and loading evaluations.

The better specimen of the two was used to evaluate the deflection characteristics, even though a large portion of the sealing lip was ground away in an effort to get a flat seal edge. Dial indicators were mounted at points A, B, and C at the corner, as shown in Figure III-10 to detect abnormal corner action. One such abnormal action may occur when some point of the seal contacts the jamb somewhat ahead of the balance of the seal. The corner may then advance toward the jamb ahead of other portions of the seal not yet in contact with the jamb.

The specimen was lowered into contact with the simulated jamb surface. Initial contact occurred at the Number 2 end, as shown in Figure III-10. The gaps at the other locations are also shown in this figure.

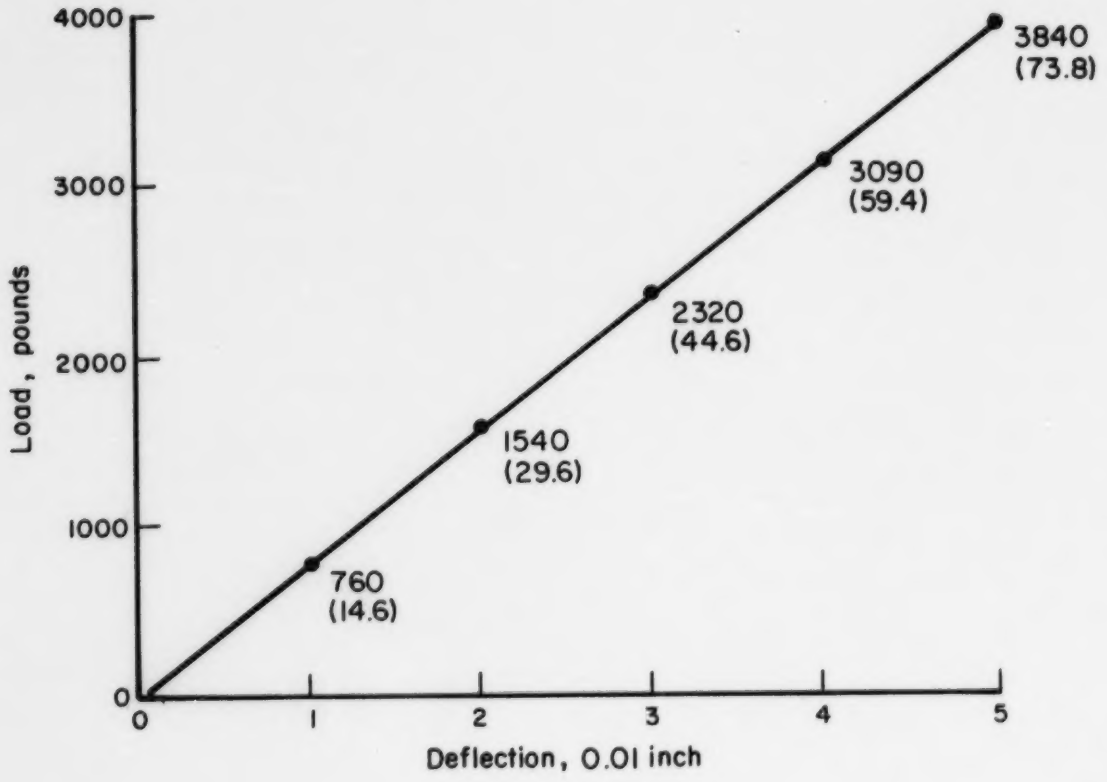
A load of 9 kg (20 lb) brought end number 1 and the seal under the dial at point C into contact with the jamb surface.

TABLE III-6. LOADINGS ON 52-INCH STRAIGHT SPECIMEN SEAL

Condition of Bow in 14-Foot Length, in.	Deflection, in.				
	0.10	0.20	0.30	0.40	0.50
Straight	800 (15.4)	1600 (30.8)	2400 (46.2)	3100 (59.6)	3880 (74.6)
0.50	750 (14.4)	1560 (30.0)	2350 (45.2)	3120 (60.0)	3900 (75.0)
0.60	750 (14.4)	1540 (29.6)	2320 (44.6)	3120 (60.0)	3870 (74.4)
0.70	760 (14.6)	1550 (29.8)	2340 (45.0)	3120 (60.0)	3870 (74.4)
0.80	740 (14.2)	1540 (29.6)	2340 (45.0)	3100 (59.6)	3850 (74.0)
0.90	780 (15.0)	1560 (30.0)	2350 (45.2)	3100 (59.6)	3850 (74.0)
1.00	760 (14.6)	1540 (29.6)	2320 (44.6)	3090 (59.4)	3840 (73.8)
Straight With Backup	1100 (21.2)	2520 (48.5)	3840 (73.8)	5140 (98.8)	X

Note: Numbers in parentheses are pounds per lineal inch.

1 inch = 25.4 mm.
1 lb/in. = .178 kg/cm.



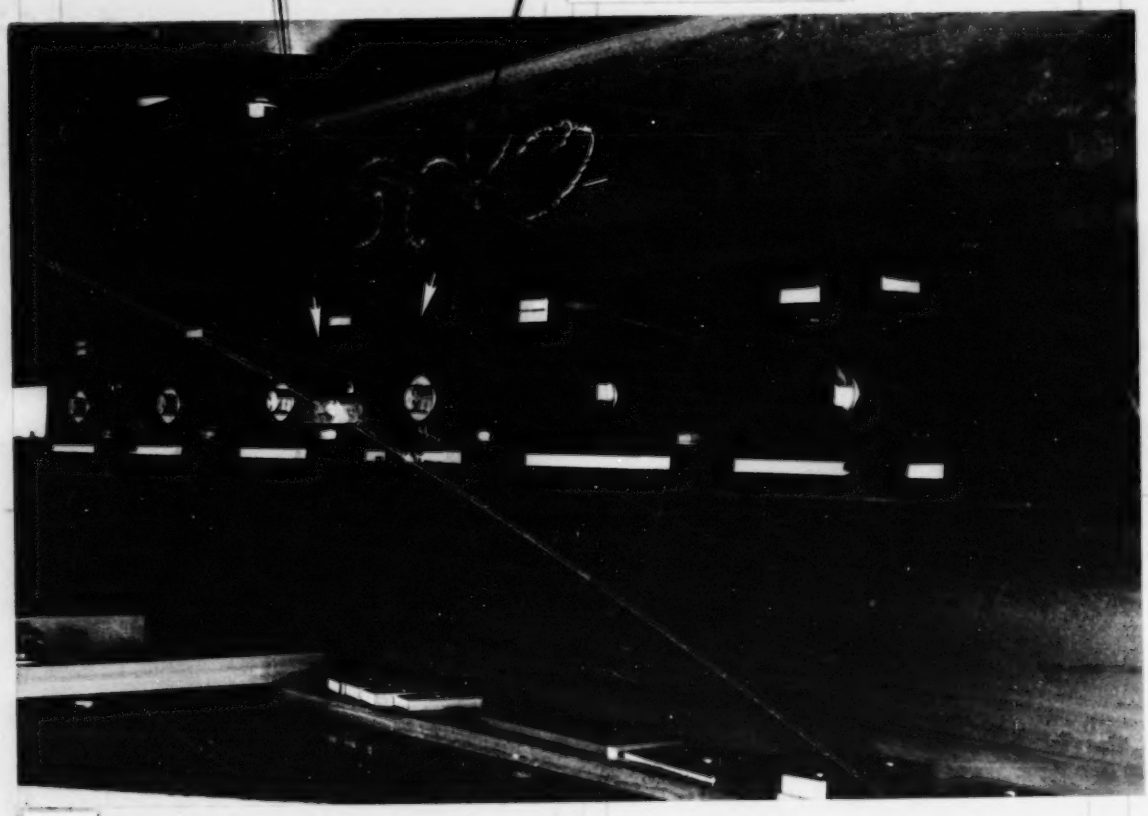
2.2 lb = 1 kg 1 lb/in. = 0.178 kg/cm 0.01 in. = 0.254 mm

FIGURE III-7. TYPICAL DEFLECTION/LOAD PLOT

1 inch in 14 feet equivalent bow

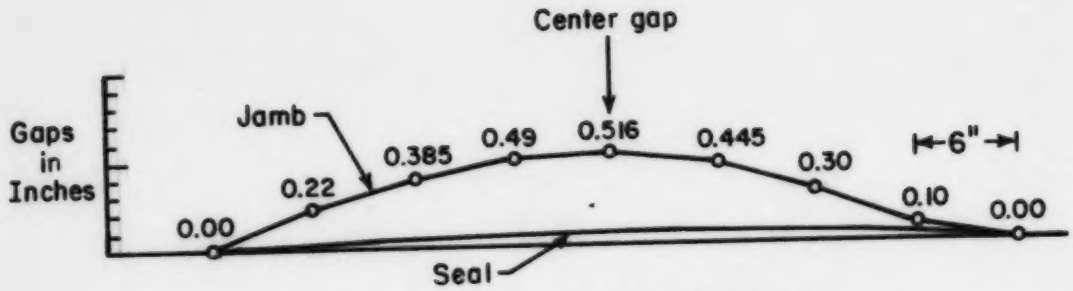
.50 deflection

Numbers in parentheses (44.6) are pounds per linear inch of seal.



#1310

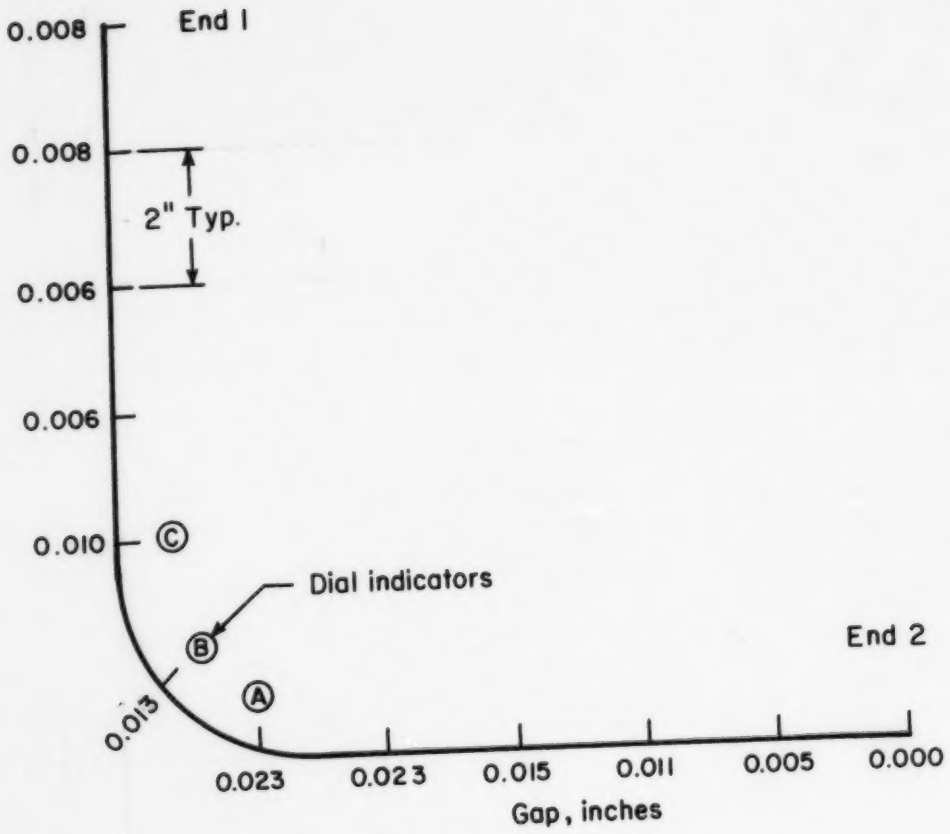
FIGURE III-8. SEVERE BOW SET INTO JAMB



Deflection		Load		Gap	
mm	(in.)	kg	(lb)	mm	(in.)
0.0	(0.00)	0.0	(0)	13.1	(0.516)
2.5	(0.10)	56.7	(125)	11.0	(0.434)
5.1	(0.20)	140.5	(310)	8.1	(0.320)
7.6	(0.30)	262.9	(580)	5.5	(0.217)
10.2	(0.40)	399.8	(882)	3.0	(0.118)
12.7	(0.50)	583.0	(1286)	0.7	(0.028)

FIGURE III-9. SEVERE IRREGULAR BOW ESTABLISHED IN JAMB

III-24



1 inch = 25.4 mm

FIGURE III-10. GAPS BETWEEN CORNER SPECIMEN AND JAMB

The seal was deflected in increments as shown in Table III-7. At various intervals, also shown in the table, the seal was released to return to the original condition. Loads, dial readings, and gaps are also shown in the table.

The dial indicators showed advancement of the corner ahead of the rest of the seal. This advance was only momentary. With continued seal loading the corner and seal deflected uniformly.

Dial indicators could not provide a true measure of seal deflection inasmuch as the seal surface constantly changed its angular relation to the indicator spindle as the seal was deflected. Indicators on the testing machine recorded the actual deflection.

A study of Table III-7 shows that yielding of the specimen began in the first 5 mm (0.20 in.) of deflection.

An additional evaluation involved the repeatability of seal action when a given deflection was applied and released several times. The results of the repetitive evaluation are shown in Table III-8. After an initial small yield occurred in the first deflection to 10 mm (0.40 in.), a uniform deflection of 10 mm (0.40 in.) was obtained having approximately the same load each time. Ends 1 and 2 and Point A closed each time, while Point B had a gap of 0.05 mm (0.002 in.), and Point C had gaps of 0.07 and .10 mm (0.003 and 0.004 in.). Each time the seal was released to the initial contact (End 1) condition, the gaps at End 2 and Points A, B, and C were approximately the same. The slight difference in the gaps before and after initial deflection is attributed to take-up in the system.

As part of the testing of the near-standard corner of an S-shaped seal (made of Inconel X-750), the metal was coated with brittle lacquer to reveal stress concentrations during the loading of the corner. Somewhat as would be expected, the stress patterns indicated a stress concentration at the 90 degree inside corner of the seal. The following decisions were subsequently made:

(1) To aid in the distribution of stresses in the corners during loading, it was decided to eliminate the square interior corner and replace it with a 51-mm (2-in.)-wide inside radius. See Figure III-11.

(2) Testing corners only has its problems. It was decided to build the bottom portion of an entire seal for testing, i.e., the section of the seal involving two corners, the standard cross piece, and portions of the side pieces. It was found nearly impossible to work Inconel X-750 by hand so the decision was made to build the new test specimen out of annealed 304 stainless steel.

This test specimen is shown mounted in the testing machine in Figure III-11. Three dial indicators were mounted at each corner to determine whether or not the corner advanced toward the jamb surface ahead of the other parts of the seal, as was detected in experiments on single corners and as reported by other investigators.

Stainless steel has a yield point of about 23 percent that of Inconel X-750 at room temperature and much less than that at 427 C (800 F). The resulting deflection needed to produce yielding could not be expected to be over 5 mm (0.20 in.). However, this specimen was used to study the

TABLE III-7. DEFLECTION OF CORNER SEAL (1) SPECIMEN, INCONEL X-750

Deflection, in.	Load, lb	End 1	End 2	Point A Gap	Point B Gap	Point C Gap
Contact		Contact	Contact	0.017	0.015	Contact
0.025	100					
0.100	500					
0.200	880					
Release				0.030	0.027	0.010
0.300	1373				0.002	0.007
Release				0.061	0.057	0.035
0.400	1870	0.002	0.008			0.013
Release				0.100	0.095	0.071
0.500	2330			slight gap toward 2	0.001	0.017 midpoint 13-C
						0.006
Release		0.024	0.027	0.150	0.141	0.111 midpoint B-6
						0.124

(1) Poor-quality corner seal specimen received from one fabricator.

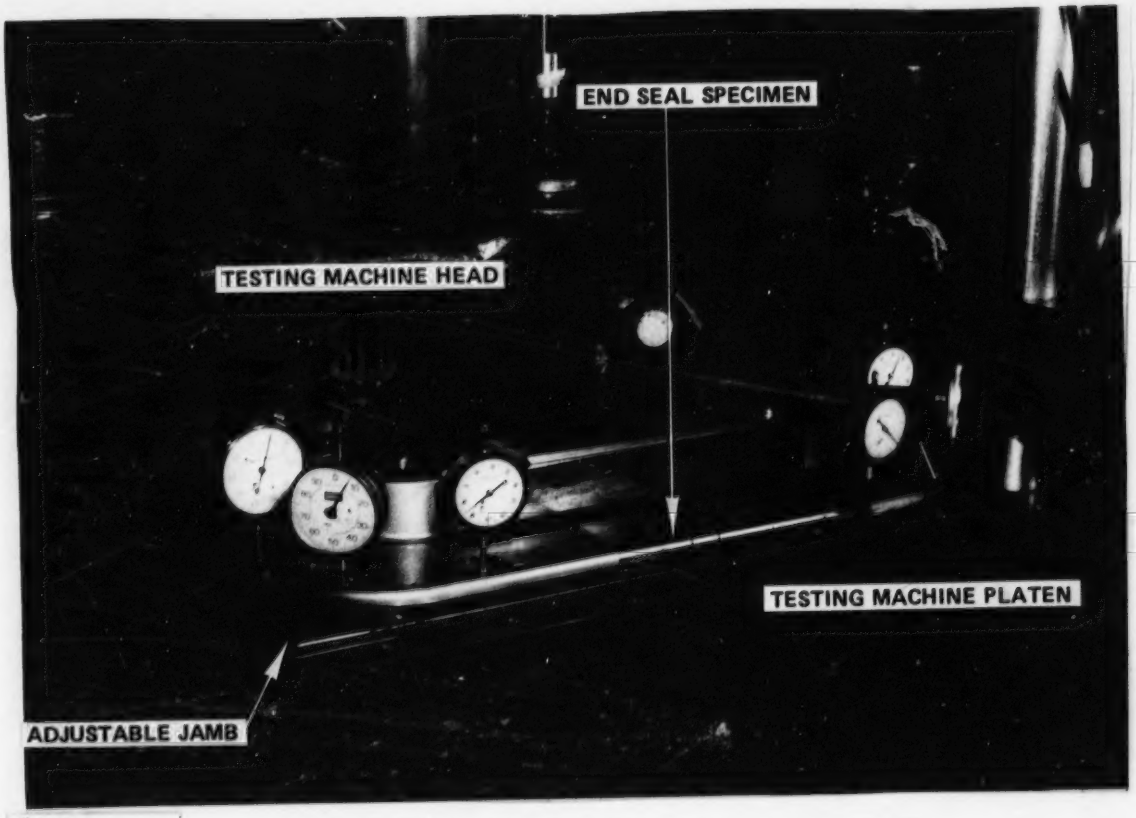
Comment: Application of brittle lacquer on this specimen to reveal stress concentration and stress patterns indicated a not unexpected stress concentration at the 90 degree inside corner of the seal. The design was modified as discussed in the following text.

1 inch = 25.4 mm.
1 pound = 0.45 kg.

TABLE III-8. REPETITIVE DEFLECTION OF CORNER SEAL SPECIMEN

Deflection, in.	Load, lb	End 1	End 2	Point A Gap	Point B Gap	Point C Gap
Initial contact		0	0.019	0.107	0.095	0.067
0.40	1840	0	0.000	0.000	0.002	0.003
0		0	0.031	0.119	0.115	0.078
0.40	1828	0	0	0.000	0.002	0.004
0		0	0.030	0.122	0.118	0.078
0.40	1826	0	0	0.000	0.002	0.004
0		0	0.030	0.123	0.116	0.076
0.40	1814	0	0	0.000	0.002	0.004
0		0	0.029	0.123	0.118	0.082
0.40	1795	0	0	0	0.002	0.003
0		0	0.031	0.129	0.122	0.084

Note: 1 inch = 25.4 mm.



#1502

FIGURE III-11. SEALING RING END SPECIMEN

action of the deflecting seal corner of the recommended design geometry. Deflection capability was established in the high-temperature evaluations using 25-mm (1-in.)-wide specimens.

Reference points were established on the end specimen, as shown in Figure III-12, using dial indicators positioned at the corner points (10, 12, 14, and 21, 23, 25). The seal edge, as fabricated, was not perfectly flat, but a decision was made to perform the evaluations with no attempt to improve the flatness by machining or grinding.

Several preliminary deflections of the specimen end seal were made in order to observe its general reactions. Brittle lacquer was then applied to the underside (oven side) of the specimen. Deflection of the seal produced the stress pattern shown in Figure III-13. Pattern lines are at right angles to the stresses. While the stresses are still somewhat concentrated at the corner, they blend into the stresses along the straight sides, *demonstrating the need for the 51-mm (2-in.) inside radius in order to minimize the stress riser effect of the conventional, square corner.*

The specimen then was subjected to deflections in increments of 2.5 to 7.6 mm (0.10 in. to 0.30 in.) total deflection. At each 2.5 mm (0.10 in.) of deflection, gap measurements and strain gage readings were taken. Initial gap measurements were made with the seal in contact with the simulated jamb at points 16 and 17. Gap readings are shown in Table III-9 and are plotted in Figure III-14. Yielding of the stainless steel specimen is shown in these data by the differences in beginning and release gap readings shown in Table III-6 and the curves depicted in Figure III-14.

[The data presented in Table III-9 and in Figure III-14 were interpreted at the time as being evidence of a high degree of seal edge (corner) flexibility/conformability because initial gaps readily closed on deflecting the seal (as in the mounting of a door on an oven). Particularly impressive was the near closure of gaps upon deflecting the seal only 2.5 mm (0.1 in.). However, the corner action of demonstration seals did not replicate the gap closing actions shown in the above data. In fact, complete seals fabricated of Inconel X-750 (and then hardened to maximum tensile strength) show a definite tendency to open up corner gaps upon seal deflection. This point is raised here because the reader may wish to return to a study of these data after reading the results of field testing of complete seals. In this report, the progression is chronological and will therefore continue with the conclusions drawn at the time of the testing.]

Conclusions on Seal Flexibility

The foregoing discussion describes the procedures used in the flexibility evaluations and the results presented in each case. Favorable conclusions about the recommended seal design may be made on the basis of the evaluation results. These conclusions provide assurance for the effectiveness of two features of the seal design:

- Greater flexibility of the sides of the seal along the jamb sealing surface than is attained with conventional seal designs
- Improved flexibility of the newly designed corner over that of conventional corner designs.

III-30

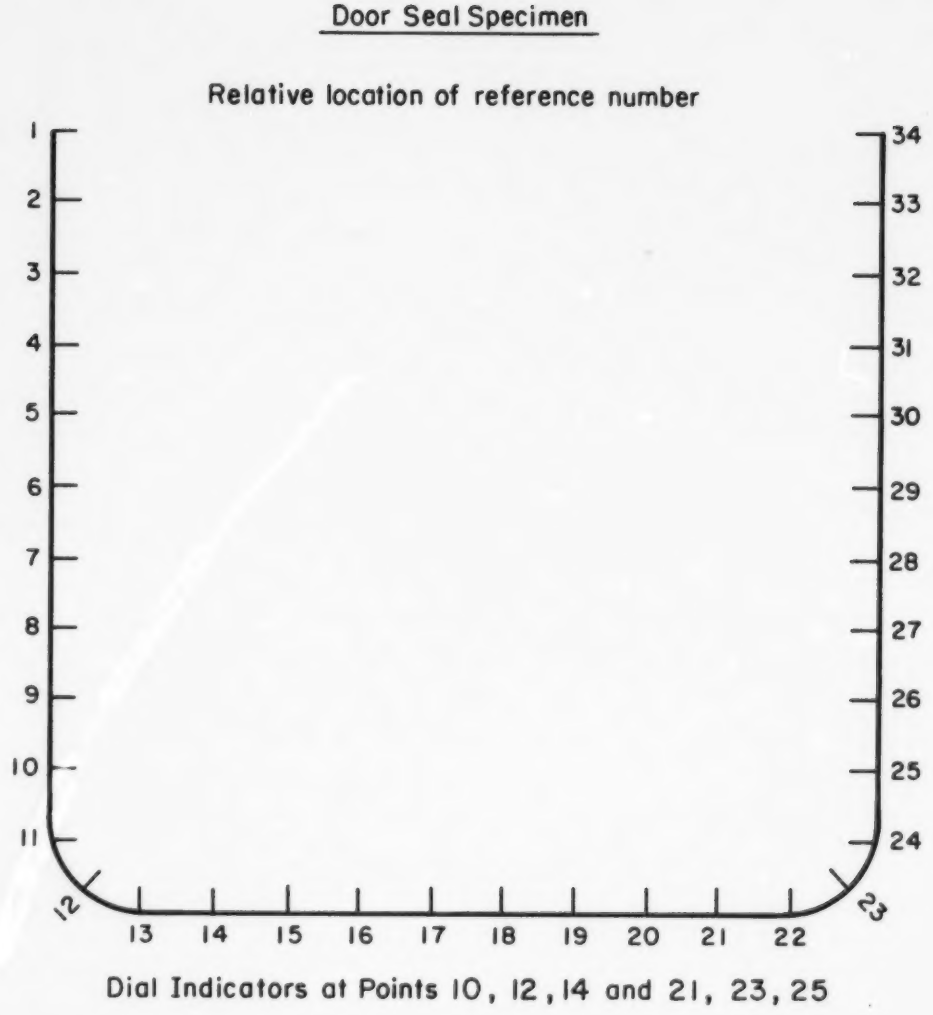


FIGURE III-12. REFERENCE POINTS ON END SPECIMEN SEAL

#1550

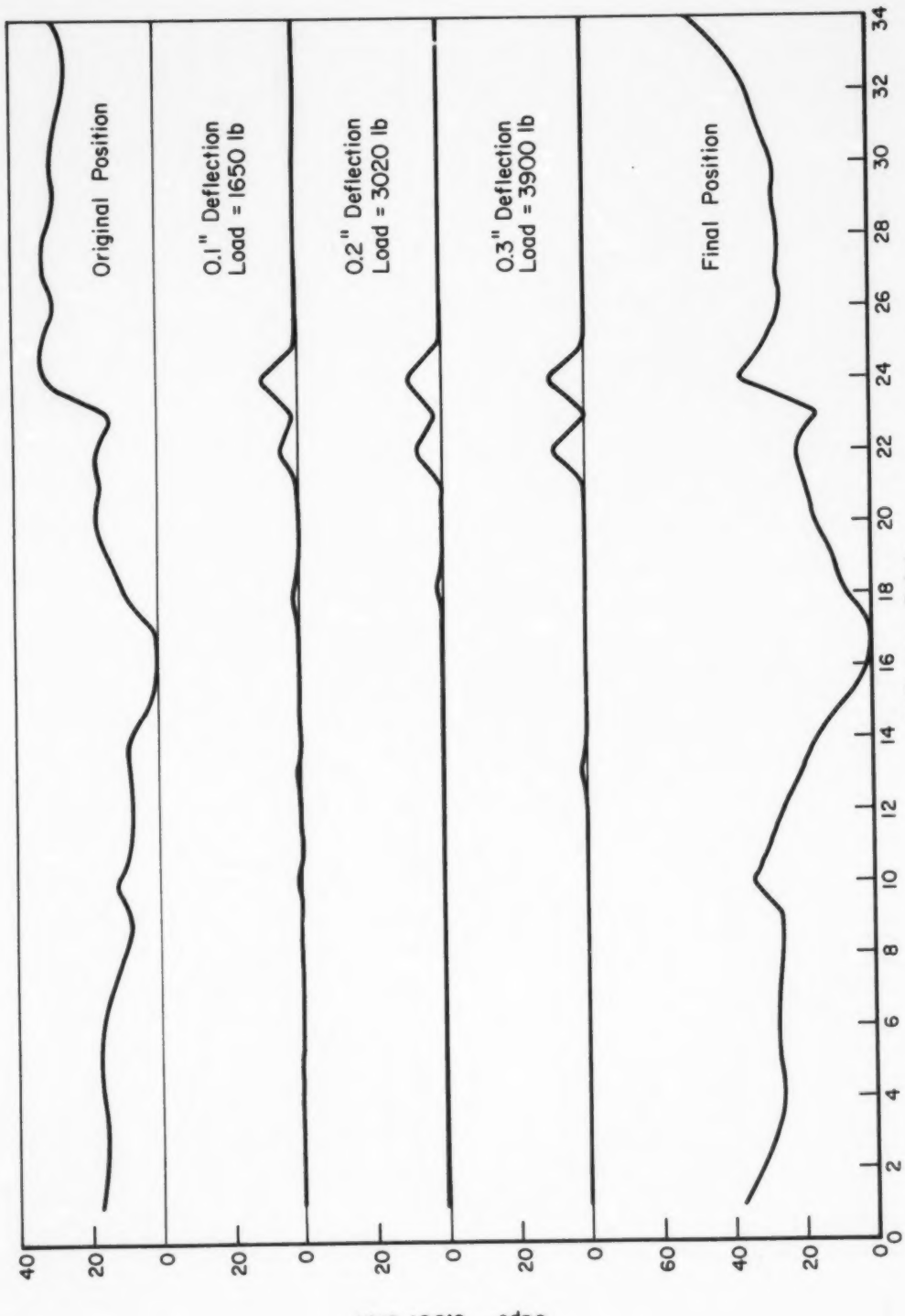
FIGURE III-13. BRITTLE LACQUER STRESS PATTERN ON CORNER

Note: Pattern lines are at right angles to stresses.

TABLE III-9. GAP MEASUREMENTS – END SPECIMENS

Position	0 Gap, in.	Deflection, in. 0.1	0.2	0.3	0
1	0.017	0	0	0	0.037
2	0.016	0	0	0	0.031
3	0.015	0	0	0	0.028
4	0.016	0	0	0	0.026
5	0.017	0	0	0	0.027
6	0.016	0	0	0	0.027
7	0.014	0	0	0	0.027
8	0.010	0	0	0	0.026
9	0.008	0	0	0	0.026
10	0.012	0.001	0	0	0.034
11	0.008	0	0	0	0.029
12	0.007	0	0	0	0.025
13	0.008	0.001	0	0.002	0.020
14	0.008	0	0	0	0.016
15	0.002	0	0	0	0.008
16	0.000	0	0	0	0.001
17	0.000	0	0	0	0
18	0.009	0.002	0.001	0	0.007
19	0.013	0	0	0	0.011
20	0.017	0	0	0	0.016
21	0.016	0	0	0	0.018
22	0.017	0.006	0.008	0.009	0.021
23	0.013	0.002	0.002	0	0.015
24	0.031	0.011	0.011	0.010	0.037
25	0.032	0	0	0	0.030
26	0.028	0	0	0	0.025
27	0.031	0	0	0	0.026
28	0.031	0	0	0	0.026
29	0.028	0	0	0	0.027
30	0.029	0	0	0	0.027
31	0.027	0	0	0	0.031
32	0.025	0	0	0	0.034
33	0.025	0	0	0	0.040
34	0.028	0	0	0	0.050
Load, lb		1650	3020	3900	

Note: Figure III-14 has these data plotted.
1 inch = 25.4 mm.



1 inch = 25.4 mm
1 lb = 0.45 kg

FIGURE III-14. PLOT OF GAPS AT SEVERAL DEFLECTIONS

Sides. The flexibility of the recommended seal along the jamb seal surface is the result of two design features. The first feature is the narrow 9.5 mm (3/8 in.) sealing edge which, by inspection verified using conventional formulae, *is more flexible than one of the convention design by almost an order of magnitude.* The other feature is the method of mounting which shapes the seal to be congruent with the jamb sealing surface. When congruent with the jamb, no part of the seal is required to deflect excessively and no part remains undeflected less than that required to effect a seal.

The evaluations demonstrated that the sealing ring, when mounted in a congruent manner, could be deflected adequately in order to achieve a condition of sealing having a reserve deflection capability. The limits of this capability were not determined in the evaluations.

Corners. Corners of the sealing rings are inherently less flexible than are the straight portions of the recommended seal. Two features of the corner design of the recommended seal greatly improve the corner condition. A radius at the inside corner reduces the stress raiser effect of a square corner. The stresses are spread out by the radius and blended into the stress pattern along the sides. The corner is further improved by the method of fabrication. A hydroformed corner requires no welds and therefore consists of homogeneous material uninterrupted by weld lines. In addition, it is considered probable that the seal edge of the hydroformed corners can be made very flat by employing a finishing, side-cutting operation. This should give improved flatness when compared to the process of machining or grinding on the top of the spring upstanding edge. The specimen corners could not be formed by hydroforming because of tooling costs.

The evaluations demonstrated that the corners, as designed and fabricated, did function satisfactorily.

Full-Scale Seal Design

The requirement of this subtask was to develop engineering drawings of the recommended seal as well as preparing text for the Request for Quotation sent to five fabricators. This section presents some of the text that was included in the Request for Quotation. Engineering drawings, however, are not included in this report.

Introductory Comments

A requirement of this task is to provide a seal that can be retrofitted to existing coke-oven doors with no change or modification to door frames, jambs, latches, or other components. Preliminary studies indicated that a typical Koppers battery would permit the first simplest retrofitable design. A Wilputte oven-door retrofit requires a greater amount of preparation than does a Koppers

retrofit and was, therefore, completed after the Koppers retrofit design. Basic features of the sealing ring, such as cross-section shape, material, and corner design, are the same for retrofits to either type of battery.

The cross-section shape, with the optional backup spring leaf and *without* the conventional Koppers spring plungers, should achieve a near uniform sealing pressure around the sealing ring. Such variations, which do occur in sealing pressure, are attributed to two factors:

- Differences in deflection of sealing rings because of changing jamb or door profiles
- Fabrication variation.

The sealing ring is intended to be mounted to the door frame in a manner such that it is shaped to a near congruent fit with a warped jamb. Subsequent changes of the jamb or door profile will disturb the original seal/jamb fit, resulting in nonuniform deflection of the seal. Therefore, points points of greater seal deflection will result in higher sealing pressure; points of smaller seal deflection will result in lower sealing pressure.

Fabrication variations may result in a sealing edge that is not straight. Laboratory evaluations demonstrate that such variations may close on the jamb just as they would if the variations existed in the jamb rather than the sealing ring. The specified flatness limits of the variations along the jamb-contacting seal edge are (a) for the straight sides – 1.6 mm in any 1.2 m (1/16 in. in any 4 ft) and (b) for the corners – 0.016 mm in 1.2 m (0.003 in. in 12 in.). The seal edge for the straight side is allowed to have a bow following fabrication. It is expected that this condition will be eliminated when the seal is bolted to its support angle. Verification of the seal tolerances will be made during the demonstration project.

Another feature of the sealing ring is seen in the cross-section shape (Figure III-15). The sealing edge lip is narrower, 9.5 mm (3/8 in.), than the typical Koppers lip, which is about 25 mm (1 in.). The shorter lip will provide greater flexibility of the seal along the jamb resulting in greater ability to accommodate any jamb irregularities and manufacturing variations in the sealing ring.

An important feature of the design is the selection of a material that maintains desirable operating characteristics of 427 C (800 F). Such a material is Inconel X-750, which is available in quantities suitable for demonstration purposes. Inconel X-750 requires more care in fabrication than required of materials presently used in end closures. This care is required mostly in welding and heat treatment. These features are described in detail later.

The corners of the sealing rings have the same basic cross section as the straight portions of the seal. The addition of a 51 mm (2 in.) inside radius aids in maintaining the cross-section shape around the corner and reduces the concentration of stresses at the corner to acceptable limits.

As part of the design effort, methods of fabricating the sealing ring were investigated. Some of the methods are new to the suppliers to the coke-producing industry but are common in other segments of industry.

The corners are preferably made by hydroforming, which is described in more detail elsewhere in this report. The corners can be made by cutting, forming, and welding as is currently the practice with Koppers seals. However, an appreciable reduction of seal quality will result, as observed in the

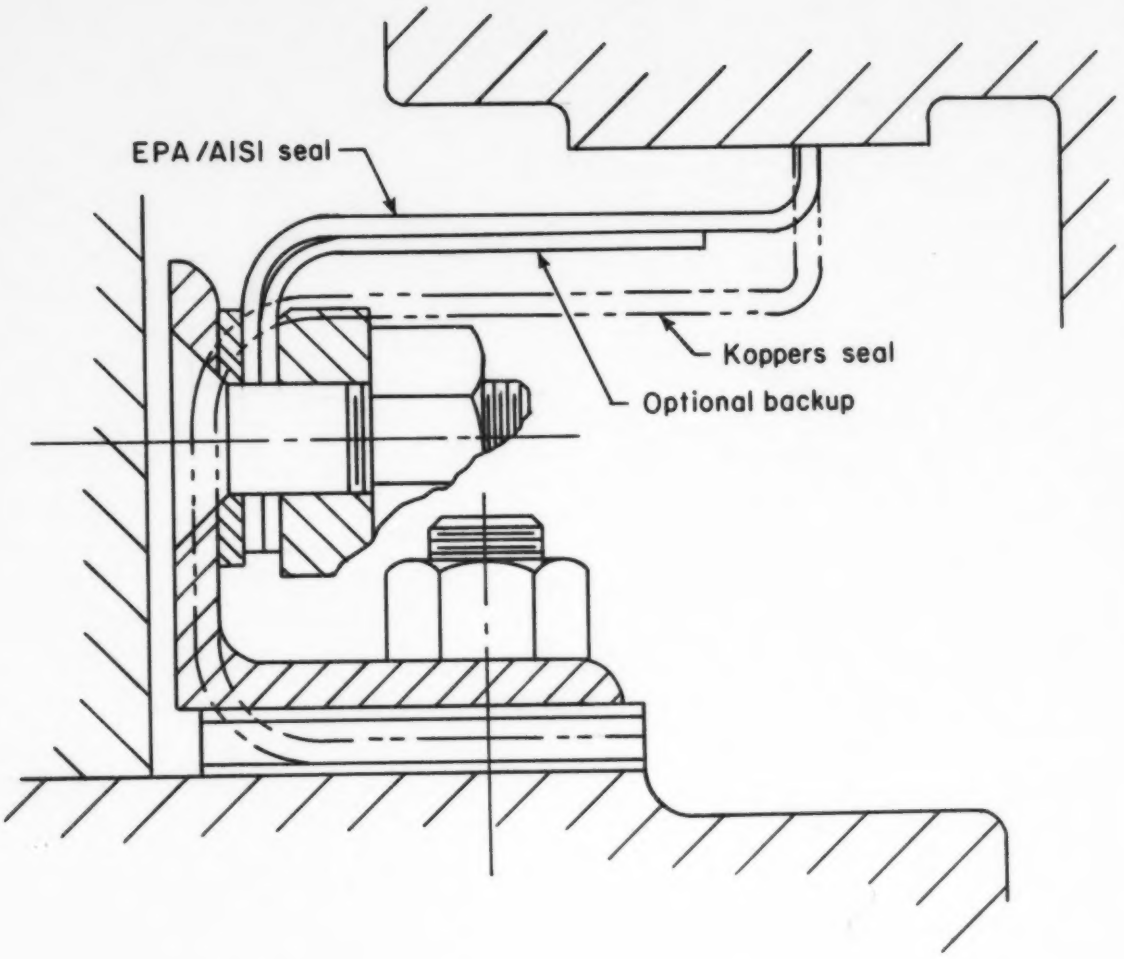


FIGURE III-15. COMPARISON OF EPA/AISI SEAL AND CONVENTIONAL KOPPERS SEAL

laboratory evaluations conducted during this task. Consequently, this conventional method is not advisable, and the use of hydroformed corners is recommended.

The straight sides and ends of this EPA/AISI seal may be formed using conventional press brake operations. If large quantities of sealing rings are to be made (four to six batteries), roll forming should be considered. Roll forming results in a greater product uniformity than can be expected using press brake operations, and lower cost.

Figure III-15 compares the EPA/AISI retrofitable seal with a typical Koppers seal, and Figure III-16 compares the new seal with a typical Wilputte seal.

Seal Design

The recommended seal has a large and fairly uniform deflection capability that will accommodate most warped door and jamb combinations. Two benefits are expected to result when this seal is used; (1) only broken and severely warped doors and jambs will need to be replaced, (2) satisfactory performance may be achieved with larger fabrication tolerances than are customary for sealing rings. A number of factors are necessary for the successful application of this seal design at coke plants. These factors may be divided into three groups:

Design

- Geometry
- Material
- Tolerances

Fabrication

- Forming straight sections
- Forming corners
- Welding
- Machining
- Grinding
- Heat treatment
- Assembly
- Workmanship

Quality

- Records
- Inspection and acceptance.

Design

Geometry. A large deflection capability is achieved by the geometric form of the sealing ring when selected materials are used. Figure III-15 shows that the seal is similar in cross section to that of the conventional Koppers seal, except that it has two bends instead of three and the sealing lip is

9.5 mm (3/8 in.) in height instead of 25 mm (1 in.). A further inspection of the drawings will show that the cross section of the seal continues around the corners and across the top and bottom with little change. As with the conventional Koppers seal, the seal is wider across the top and bottom than it is along the vertical sides. This feature is retained to simplify the retrofit of the seal to Koppers doors. Figure III-16 shows that the same sealing ring design may be retrofitted to Wilputte end closures.

Figures III-15 and III-16 also show an optional backup strip which gives the seal a spring action somewhat similar to that of leaf springs of an automobile. While the sealing ring is continuous all around, *the backup strips are straight sections that do not pass around the corners.* The sealing effect is not dependent upon the backup strips that are added to the seal to resist the normal latching forces to be found on a battery. If all doors on a battery had this seal, the strips could be left off and the door-handling machinery could be adjusted in order to apply smaller latching loads. All backup spring plungers mounted in the conventional Koppers door frame have been eliminated to permit a continuous spring action around the seal. This creates a nearly uniform sealing force that varies only as the seal deflection varies.

This design, when fabricated using proper materials and mounted on the door frame, as described later, permits a large deflection before damage to the seal can result.

Flexibility along the jamb surfaces parallel to the seal edge is achieved by reducing the height of the sealing lip from the customary 25 mm (1 in.) on Koppers seals to about 9.5 mm (3/8 in.) on the proposed seal. Thus, the proposed seal has increased flexibility along the jamb and greater deflection capability in the cross section than is found in the typical Koppers seal. This seal, when used on a Wilputte end closure, replaced the rigid sealing edge with a flexible edge.

Material

The material presently proposed for this seal is Inconel X-750, supplied by Huntington Alloys of Huntington, West Virginia, through their various distributors. The present design calls for material that is 2.4-mm (0.093-in.) thick or Number 13 US gage. Later, other gages may be employed. Huntington Alloys provides pamphlets describing this material and the various working procedures that are necessary to fabricate it. They are available on request to Huntington.

Tolerances

One goal of this project is to relax the tolerances that have customarily been shown on sealing ring drawings. Less critical tolerances make fabrication easier and can reduce costs. Laboratory evaluations at Battelle indicate that these tolerances can be relaxed. Evaluations of the seal indicate that, within some as yet undefined limits, the seal does not differentiate between the imperfections of its sealing edge or imperfections of the jamb sealing surface. The limits of this self-correcting capability will be evaluated and more accurately determined in the full-size demonstrations.

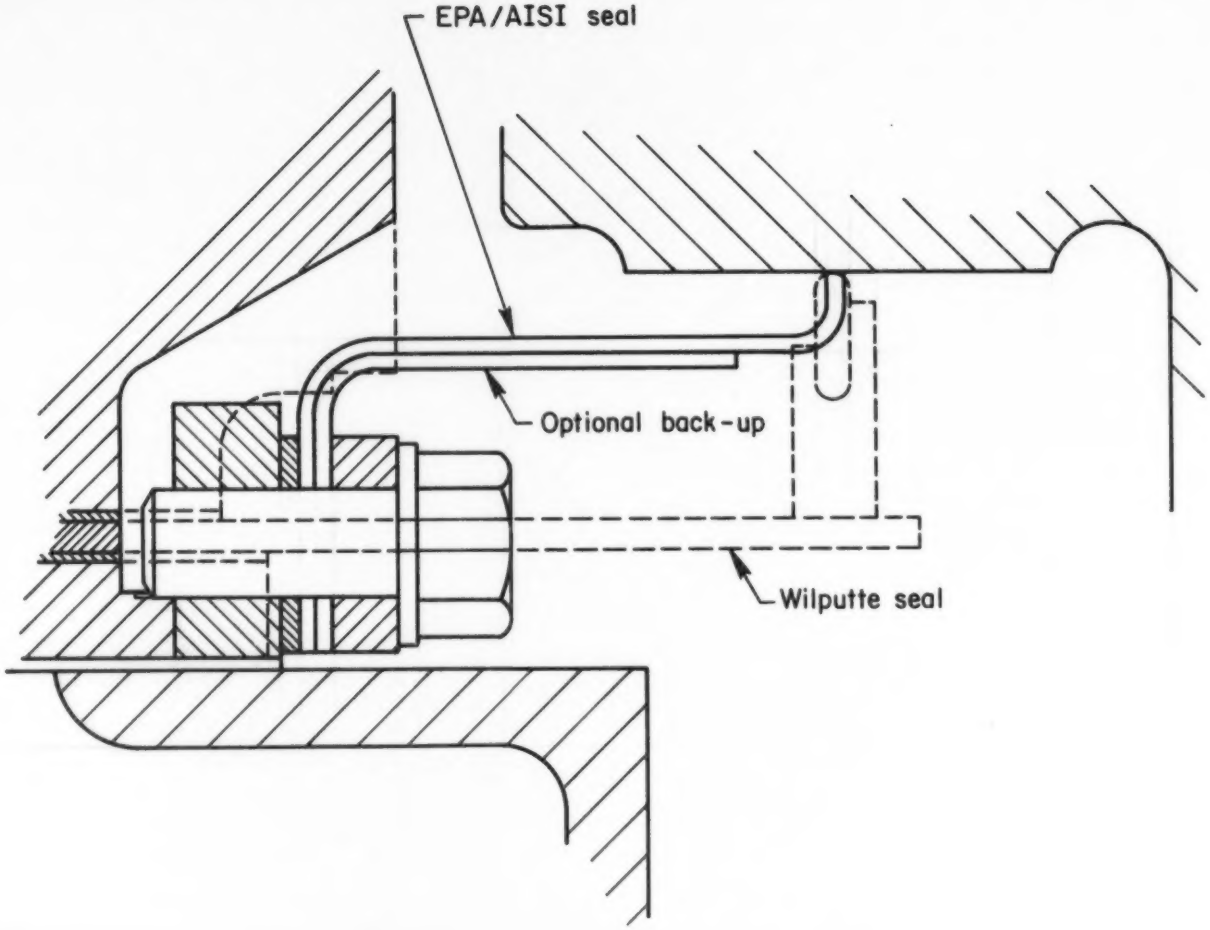


FIGURE III-16. COMPARISON OF EPA/AISI SEAL AND CONVENTIONAL WILPUTTE SEAL

While one goal is to relax tolerances, development work requires that prototypes be fabricated with as close tolerances as possible. This practice reduces the variables to consider in field evaluation of the prototypes and determines fabrication capability. As experience is gained in fabrication and use of the sealing rings, a more reliable analysis of tolerances can be made. The tolerances shown on the enclosed drawings are starting values based on present, limited knowledge. Experience gained in the demonstration tasks may be used to redefine these tolerances, hopefully relaxing them rather than tightening them.

Fabrication

Forming Straight Sections

The customary method used to form straight sections of Koppers seals employs a press brake. All the required dies are standard and are available from press brake manufacturers. Roll forming appears to be the preferable method used to form the straight sections when large quantities of seals are required. Better uniformity and lower cost may be expected with roll forming than with press brake forming. Preliminary estimates from roll formers indicate that an economical run would provide the straight sides for sealing rings for four to six batteries. Some roll formers have capability for punching holes in the roll-formed sections as they are produced. Variation in hole patterns from battery to battery may present a problem in using this capability.

Forming Corners

Corners are a critical part of any sealing ring. Hydroforming is the preferred method for forming the corners of this new seal design. Using this method, a can is formed as shown in Drawing 000-504-388. The hydroformers trim the edges and separate the corners to obtain a set of four corners for each sealing ring. When this method is used, corner welds are moved to the straight portions of the sealing ring and a uniform material section can be maintained around each corner. Furthermore, the corners made by this method will display minimal metal thinning. The conventional method of cutting, forming, and welding is not desirable for the corners of this seal. Every effort should be made to obtain good corners. Other methods of forming the corners may be tried, such as hard tooling or spinning. Corners made by spinning will be welded to the straight portions of the sealing ring at the tangent line. This weld location is less satisfactory than one being an inch or more from the tangent line, as with hydroformed corners.

Welding

Welding, as shown in the Huntington pamphlets, employs the gas tungsten arc welding method, using their filler rod 69. Further, Huntington recommends that welding on material of the gage

used in the seals be carried out on both sides. Upon completion of the first weld, the opposite surface sould be well cleaned before that side's weld is applied. Weld beads are then ground flush, resulting in a flat surface. The use of hydroformed corners, as described above, simplifies and enhances the welds that are moved away from the corner. Simple butt welds are employed here.

Machining

Three reasons may exist for machining the seal. One is to reduce the formed sealing lip to the 9.5-mm (3/8-in.) dimension.(1) The second is to true an edge that is not straight within tolerance. The third is to prepare an edge in the flat to facilitate greater accuracy in the bending operation. A goal of this seal design is to reduce the machining required, or do away with it entirely. If fabrication methods, as described, are successful in maintaining acceptable tolerances, then the only machining that may be required would be to prepare the sealing edge after it has been sheared from flat stock. In this case, a number of sheets can be stacked in the flat and machined during one pass of the machine. *A specific goal of the seal design is to avoid machining the seal edge after forming* – holding fixtures tend to distort the seal while it is being machined. Return of the seal to its free state upon removal from the fixture results in irregularities in the seal edge, i.e., machining may introduce new problems while attempting to obtain a "straight edge".

Grinding

Grinding will be necessary at the welds, particularly on the sealing edge. Another form of grinding may be necessary to true the sealing edge after the sealing rings have been assembled to the sealing frame. This may be done using a large milling machine with a grinding head attached to the milling head of the machine. *This operation is considered strictly a finishing operation.* Holding the work for grinding has the same problems as that for machining the seal edge. Grinding should be used to remove a minimum amount of material.

Heat Treatment

Two heat treatments are required in the fabrication of this seal. The first is a fast solution annealing for all of the welds. This consists of *rapidly* heating the welds to 983 C (1800 F) or higher for about 15 minutes, followed by air cooling. Battelle has demonstrated that the ends of the seal (location of the welds) can be immersed in a molten salt heat-treating bath (for solution annealing of the welds) without resulting in distortion. Heating of the entire seal to 983 C (1800 F) is not recommended.

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(1) There is a difference of opinion among fabricators whether the 9.5-mm (3/8-in.) lip can be formed in without the need for subsequent machining to obtain this dimension. No fabricator presently has the tooling for making making a trial bend. This tooling can be obtained from the press manufacturer in two weeks at a cost of $1,100.

The second heat treatment is the aging heat treatment, which gives the material (a) its high strength and hardness level and (b) its resistance to creep and relaxation in service. The recommended procedure specifies holding the seals at 704 C (1300 F) plus or minus 5 C (10 F) in air for 20 hours, followed by air cooling. Special supports or retaining frames for the seal are not necessary during this heat treatment. Laying it flat on a hearth provides sufficient support. However, the furnace should have forced air or gas circulation in order to hold a uniform temperature on the seals during heat treatment. Some heat treaters attach a thermocouple to the work and control temperatures based on temperature information which it supplies. Other procedures for aging heat treatments may be used, but they involve greater care in timing and control of temperatures.(1)

Assembly

An important part of this seal retrofit is the assembly of the sealing ring to the ring frame. When assembly has been completed, a check must be made to assure that the assembly has not introduced undesirable variations in the sealing edge.

Workmanship

Referring once again to the nature of research and development work, a high level of workmanship is required in the fabrication of the demonstration seals. Once the seals have been evaluated in the field and their performance determined, the level of workmanship required can be reevaluated.

(1) Battelle is working with the alloy supplier to determine whether a shorter heat treatment time can be tolerated. If a shorter time is possible, a change order will be sent to all bidders.

CHAPTER IV

SUMMARY OF THE DEMONSTRATION PROJECT

Demonstration efforts were completed at two steel companies. Due to certain circumstances, the demonstration project extended over a prolonged period of time. The events that took place during this period are given below.

Chronological Order of Events in the Demonstration Project

Month and Year	Description of Event
April, 1978	At a joint meeting of the AISI Task Force on coke-oven seals with the EPA Project Officer, it was agreed that the first demonstration site would be at a coke battery at Republic Steel in Youngstown, Ohio. Details of the joint Battelle and Republic Steel efforts at the Youngstown site were discussed with personnel of Republic Steel, the AISI, and EPA.
June, 1978	An EPA/AISI/BCL Progress Report Meeting was held at Battelle in Columbus, Ohio. There was discussion dealing with (a) a second test site on Koppers equipment, (b) testing of the recommended seal at a 6-meter battery at Bethlehem Steel (Lackawanna, New York), and (c) developing a seal adaptation to a 6-meter battery at Inland Steel.
July 1978	Republic Steel ordered sheets of Inconel X-750 for use in the fabrication of four test seals.
August, 1978	Battelle recommended to the project officers that the seal corners should be made in a hydroforming operation rather than by the standard manual methods. This approach would make it possible to obtain the desired interior radius in the seal corners to avoid a stress concentration during seal deflection. This approach introduced a problem because of a tooling cost for hydroforming of $8,000 to $10,000. According to the existing contracts with EPA and AISI, Battelle could not purchase the tooling. It was suggested that the cost be shared by the coke plants that will use the tooling.

September, 1978 — At a meeting with the AISI Coke Practice Committee it was learned that the coke industry would prefer to (a) purchase seals from their present suppliers and (b) have the suppliers include the cost of the hydroforming dies in their estimate for demonstration seals. Prior to hearing this position, Battelle had been obtaining bids from non-seal-building fabriation shops because the standard suppliers of coke-oven door seals were not interested in bidding on the demonstration seals. The AISI Committee members expressed a consensus that (a) the attitude of the standard suppliers would change when the coke industry expressed an interest and (b) in the name of the AISI, Battelle should request quotations for 24 seals (4 test seals for 6 different batteries) including the cost of the hydroforming dies. At this meeting, six steel companies expressed an interest in trying the recommended seal.

September, 1978 — Battelle mailed a detailed Request for Quotation to all known fabricators of coke-oven door seals. In subsequent visits to seal fabricators, there was an indication that two fabricators were willing to bid on the demonstration seals.

December, 1978 — On the day of the December 14, 1978 workshop dealing with the demonstration seals, two telex bids were received offering to manufacture the 24 seals. The asking price was double the amount Battelle had obtained by getting quotations from individual fabricators for separate forming, welding, and heat treatment operations. The incoming bids from the standard seal fabricators indicated a 16-week delivery after the placement of a "firm" order by six different steel companies. Following the Workshop, the AISI Project Officer decided to visit the major fabricators to request rebids based on 32 seals rather than 24 seals. The fabricators were given samples of annealed Inconcel X-750 for their own testing of favorable forming characteristics of this alloy.

Huntington Alloys informed Battelle that a heavy demand had developed for 2.4-mm(0.093-in.)-thick Inconel X-750 (aerospace use). Seal bidders were asked to place a "reserve" for the next rolling of Inconel sheets.

February, 1979 — Bethlehem Steel representative reported that their Corporation had committed itself to having four AISI/EPA seals in operation on or before July 1, 1979 at the 6-meter Wilputte coke battery in Lackawanna, New York.

In order to accomplish this goal, Bethlehem Steel: (a) placed an order for a $10,000 set of hydroforming dies for delivery March 2, 1979, (b) acquired sheets of 2.4 mm (0.094 in.) Inconel X-750 from various independent warehouses across the United States, (c) had Bethlehem Steel Engineering review the method of mounting the recommended seals on Wilputte-designed coke-oven doors, and (d) placed a priority order with Koppers (Baltimore) for fabrication of the demonstration seals.

The impasse-breaking action of Bethlehem Steel resulted in this company becoming the first demonstration site.

March, 1979

The search began for seal fabricators that would bid on the remaining 28 seals for demonstration work at sites other than at the leader Bethlehem Steel. Bethlehem Steel indicated that other steel companies (and other seal suppliers) could use the hydroforming tooling that Bethlehem Steel had ordered for their seals.

Potential bidders indicated to Battelle that they would not be able to deliver a 9.5-mm (3/8-in.)-seal lip by direct forming in a brake press. Experimental work at a company in Columbus, Ohio indicated that the 9.5-mm (3/8-in.) lip could be brake formed directly and that all subsequent machining could be eliminated. All standard suppliers of seals remained doubtful of these results.

May, 1979

Battelle gave technical assistance to the fabricator building the seals for Bethlehem-Lackawanna.

July, 1979

Four 6-meter demonstration seals were delivered to Bethlehem Steel at Lackawanna, New York. At Lackawanna the seals were stored in an "inaccessible" location. Inaccessible or not, a truck damaged the seals in passing over one corner of the seals supported on piling. These seals were easily repaired at the plant of a fabricator in Columbus, Ohio.

August 1979-
January, 1980

Demonstration work at Lackawanna, New York. Problems were encountered and not resolved. See separate section of this report describing the demonstration work at Bethlehem Steel's plant in Lackawanna, New York.

March, 1980 — Four test seals were delivered to Republic Steel's coke batteries in Youngstown, Ohio. Measurement of the seals indicated that the major flatness specification had not been met on any seal. Of the 16 aggregate corners, 14 corners had a higher seal lip than other portions of the seal, i.e., the corners are high (first to touch the jamb) with resulting gaps between the corners. The dimensional specification for the demonstration seals are more "tolerant" than those used to fabricate standard S-shaped seals but these specifications were not met in this shipment. Rework discussions were started between Republic Steel Engineering and the fabricator.

May, 1980 — Based on field experiences and additional analyses, Battelle researchers proposed a new coke-door seal design for consideration by the sponsors. This design is described in the final section of this report.

September, 1980 — Test work was completed at Republic Steel in Youngstown, Ohio. All the test results at Republic are summarized in a following section of this chapter.

The decision was made by the representatives of the sponsors to hold additional work at Republic Steel in abeyance pending possible shifting of the engineering effort on the proposed new design to Inland Steel.

November, 1980 — Inland Steel Company agreed to continue the engineering/fabrication and installation effort of the proposed new seal design at their coke plant in East Chicago, Indiana.

July, 1981 — Final report on this seal project was released.

Summary of Seal Demonstration Efforts at Bethlehem Steel Corporation
(6-meter tall battery. Fixed-seal-edge type. Lackawanna, New York)

Prior to the arrival of the demonstration seals, Bethlehem Steel's coke plant supervisor had arranged to:

(a) Select the doors (and jambs) on the 6-meter battery for the demonstration effort and
(b) Carefully measure the profile of the selected jambs using the distance-from-a-plumb-line approach.

Battelle researchers then measured the variation in the jamb to door (inboard side) distance along the height of the selected door and jamb combinations.

An example of the information obtained is shown in Figure IV-1. This figure is a plot of the relative relationship of the door and jamb profile on Pusher Side 973. Note that the height of the door and jamb have been foreshortened and that the horizontal distances have been exaggerated.

From examination of Figure IV-1, it can be seen that:

(a) The jamb is bowed outward from the oven with the most pronounced jamb curvature being in the top third of the jamb. With a hypothetical reference line drawn from the top of the jamb to the bottom, the maximum outward bow is about 13 mm (0.5 in.). The lean of the reference line is the outward lean that most batteries develop over time.

(b) The door profile (A) is almost straight at operating temperature.

(c) The fixed-edge seal, in this instance, is being asked to "handle" a *variation* in jamb-to-door distance of up to 20 mm (0.8 in.).

One of the features of the recommended seal is that it can tolerate more deflection of the seal without plastic deformation (during door latching) than the standard S-shaped seal. However, the variation of about 20 mm (0.8 in.) at this particular end-closure represents an extreme incongruency.

The "problem" shown in Figure IV-1 was handled by the procedure illustration in Figure IV-2. The assumption was made that increased care in installing the door of an oven would bring the door profile in better alignment with the jamb. In a manner of speaking, this consists of forcing the door into the oven more at the bottom to bring the jamb and door profile relationship more in alignment as shown in line (A) in Figure IV-2. This still left a larger door-to-jamb distance of 17 mm (0.7 in.) at the top and 9 mm (0.35 in.) at the bottom. This is the width in the shaded areas of Figure IV-2.

This variation was handled by placing spacers under the seal prior to bolting down the seal. For example, a 19-mm (3/4-in.)bar was put under the seal at the top. On bolting down the seal, the angle-iron seal support (and the seal) were automatically bent to take the approximate profile of the jamb, i.e., as shown in line (B) in Figure IV-2.

The leakage of emissions past the backside of the seal was prevented by using a filler of ordinary furnace cement. The actual sequence was to (a) drop spacers or a bar over the door studs where "lifting" the seal was required, (b) cover the spacers and all spaces between the spacers with non-shrinking carbonaceous furnace cement, and (c) bolt down the seal with the resultant extrusion of some of the cement. This approach prevented all leakage and should be a less costly approach to seal installation than using gaskets.

First Observations of Demonstration Seal Performance

The door for push side, Oven 973, having a double-leaf demonstration seal, was put into operation on August 12, 1979. Before the oven was charged, a feeler gauge survey around the seal indicated that there were gaps between the jamb and the seal across the top and bottom horizontal portion of the seal. These openings [about 0.4 mm (0.015 in.)] were more pronounced at the corners.

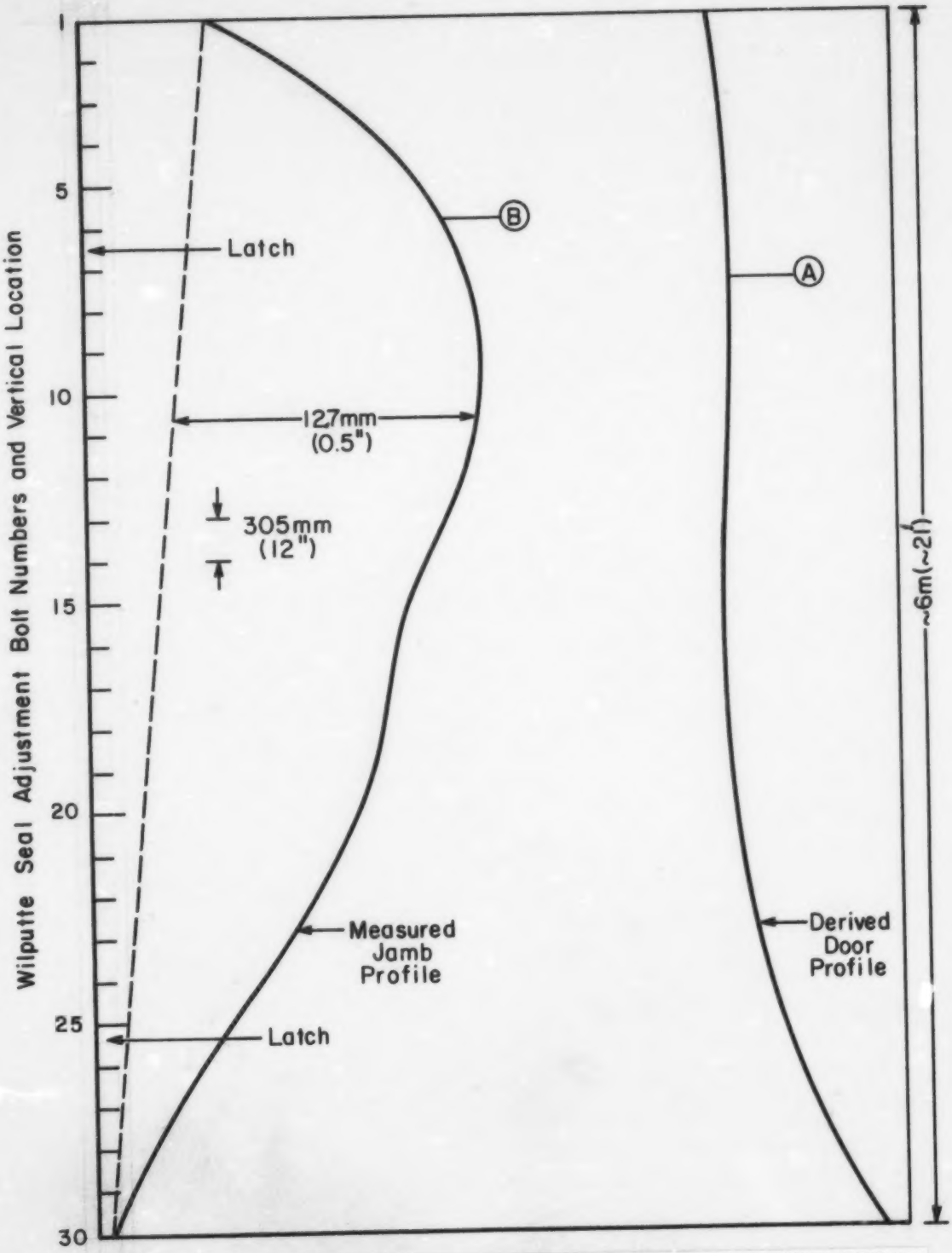


FIGURE IV-1. PLOT OF THE RELATIVE PROFILE RELATIONSHIP OF PUSHER SIDE DOOR AND JAMB (NO. 973) AT LACKAWANNA, N.Y.

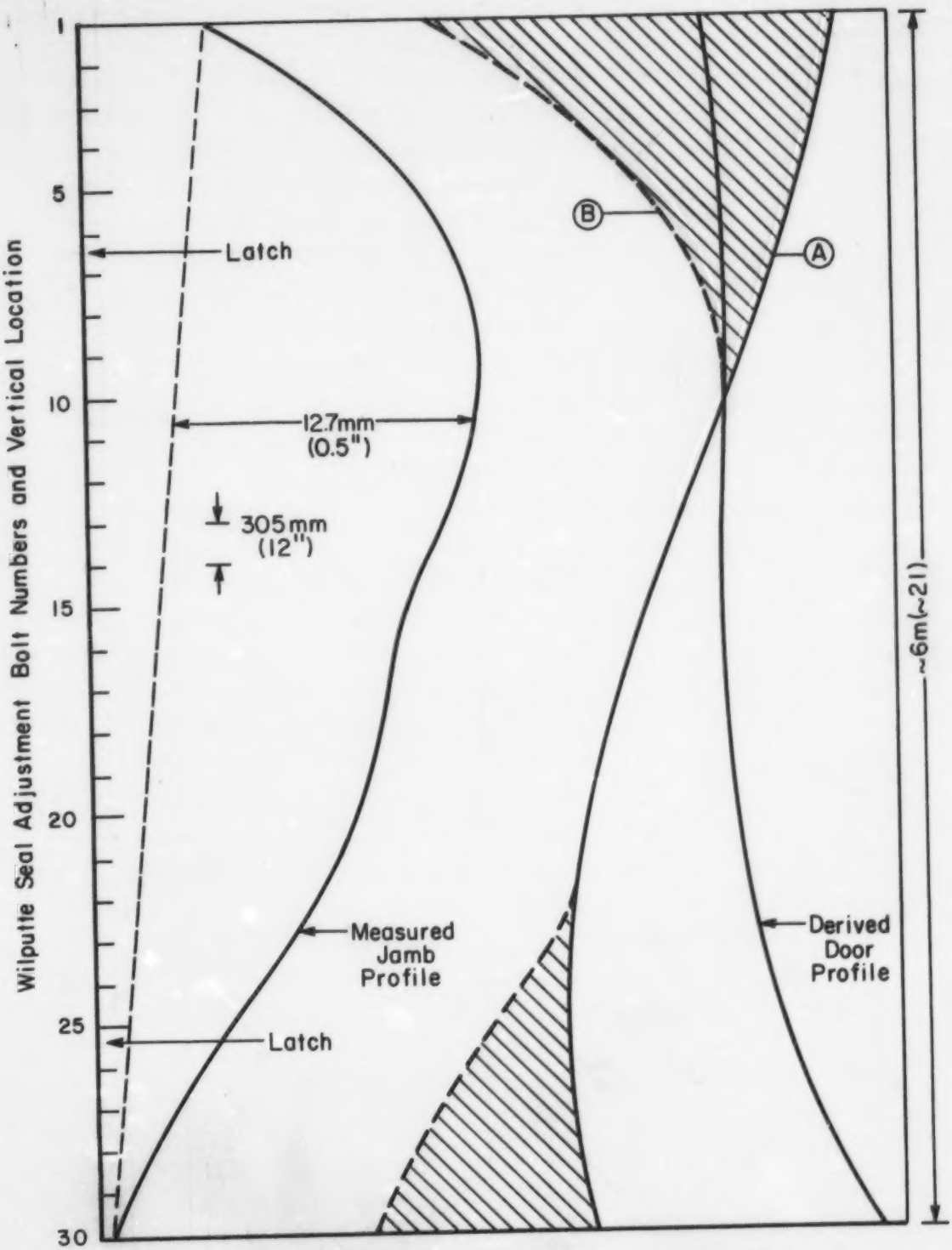


FIGURE IV-2. SKETCH SHOWING THE METHOD USED TO BRING THE SEAL EDGE AND JAMB IN APPROXIMATE ALIGNMENT (SEE TEXT)

The decision was made to charge the coal to the oven and allow the door back to come up to operating temperature. As the internal pressure built up in the door gas passage, it was noted that:

(a) The vertical sides of the seal were totally emission free, i.e., the procedure of getting the seal edge to be congruent with the warped jamb was successful along the vertical sides.

(b) There were emissions from the top and bottom horizontal portions of the seal.

The bottom and top leakage took about 2 hours to "self seal" with tar, i.e., when the oven pressure decreased, the sealing rate was about equivalent to the other doors on the battery.

On the second cycle on the demonstration seal, the emission pattern duplicated the first cycle with emissions from the top and bottom horizontal portions of the seal only. One positive observation was that the gaps had not opened up along the vertical sides of the seal as a result of the change in the door-back profile upon being heated, i.e., the change in door profile upon being heated was accommodated by the deflection of the seal.

On August 18, a second double-leaf demonstration seal was put into operation on the coke side of Oven 973. The emission control performance was identical with the seal on the pusher side with leaks only at the top and bottom portion of the seal. A third seal also gave identical performance, i.e., leaks at the corners.

In a comparison of field-trial equipment and laboratory specimens, the list of known differences were as follows:

1. In the laboratory it was not possible to test an entire seal ring. Only a full-scale bottom (or top) portion of a seal ring (0.6 meter sides) was tested.
2. The laboratory testing did not include the use of a backup or reinforcing leaf.
3. The laboratory specimen was constructed of low strength 304 stainless steel. The field-trial seal was made of age-hardened Inconel X-750.
4. Laboratory testing was done at room temperature.
5. The attachment methods differed slightly. Laboratory testing had indicated that uneven bolting of the seal to the holder could result in elastic deformation of the seal edge. Because of the design of the fixed-seal door, a modification had been introduced.
6. The seal edge in the laboratory specimen was more uneven than the edge on the field-trial equipment.

After a period of field experimentation to attempt to correct problems, the decisions were made to eliminate as many of the variables that exist between the field-trial equipment and the laboratory specimens. The steps that were taken prior to the testing of the fourth seal were as follows:

1. The first approach to retrofitting a demonstration seal to a Wilputte door was discarded. With the experience gained, it was possible to revert to the angle-iron seal holder as shown in Figure III-3.

2. The angle-iron holder for the seal was fabricated to fit the seal. This suggestion of Bethlehem Steel personnel was aimed at minimizing any elastic distortion of the seal edge during assembly of the seal to its holder.
3. The use of a reinforcing strip for the seal was abandoned. Testing of the elimination of the backup strip had been scheduled for later in the demonstration project, but was done on this test. Elimination of this strip eliminated one variable between the field-test equipment and the laboratory specimens.
4. The seal edge was machined flat after the seal was attached to its holder with particular emphasis on the corners and top and bottom portion of the seal. To eliminate the questionable practice of machining on the top edge of a spring (the seal), the machining was completed using hardened plaster to support the seal.

A tool for field use was built to measure the flatness of the seal edge (after door and seal assembly) prior to putting a door into service. Use of this tooling indicated that the reworked fourth seal intended for use on coke-side Oven 963 had only a few minor imperfections. There was a 0.2-mm (0.009-in.) gap at the north bottom corner and a 0.15-mm (0.006-in.) gap at the south bottom corner. *Loading of the tooling to deflect the seal 2.54 mm (0.1 in.) closed these corner gaps.*

The reworked demonstration seal was put into service on coke-side Oven 963 on January 15, 1980. On latching the door, the seal was deflected until most of the stop bolts were seated on the jamb giving a 7.6-mm (0.3-in.) deflection of the seal. A feeler gauge check prior to charging coal to the oven indicated a gap of 0.1 mm (0.004 in.) at both bottom corners. These gaps were rather uniform in width from tangent point to tangent point on each corner. Upon charging coal to the oven there were small leaks at the corners and none along the vertical sides of the seal. This emission pattern repeated itself on subsequent cycles on this oven.

It was concluded that the corner leakage problem encountered in this demonstration effort is not the result of unevenness introduced into the seal edge either during seal fabrication or seal mounting. It was judged that there is a flaw in the design of the seal corner relevant to our conceptual objectives.

Laboratory Efforts Dealing with the Corner Problem

The basis of the confidence in the recommended design of the corners of the demonstration seal was the laboratory test work completed on the stainless steel model of the end of the recommended seal described in Chapter III of this report. When a pattern of emission from the corners of the demonstration seals developed in the field, the first step taken was to retest the laboratory model. It was found that the originally reported "gap closing capability" of the seal corners could not be duplicated. The inference taken was that the stainless model had given excellent performance by yielding and the work-hardened model was now acting more like a high-strength steel. There was no evidence of "corner lift-off" but the closure shown in Figure III-14 could not be duplicated.

The next step taken was to equip the laboratory model with:

(a) 10 temperature calibrated strain gauges and

(b) Resistance heaters for heating the model.

Figure IV-3 is a photograph of this model mounted in test equipment.

Figure IV-4 shows the location of the reference numbers on this model used in the discussion in the following text.

Figure IV-5 shows the location of the strain gauges on the top of the seal.

Figure IV-6 shows the location of the strain gauges in the bottom corner of the seal.

Ambient Temperature Strain Gauge Data (Converted to Stress Data)

On deflecting the model by applying downward loads, the following data were obtained:

Test Number	1	2	3
Seal Deflection	1.3 mm (.05 in)	2.5 mm (0.10 in.)	3.8 mm (0.15 in.)
Deflection Loading	299 kg (660 lb)	680 kg (1500 lb)	1065 kg (2350 lb)
Temperature	24 C (75 F)	24 C (75 F)	24 C (75 F)

	Test Number					
	1		2		3	
Strain Gauge Number	Calculated Stress Data in MPa and (Ksi)					
	Tension	Compression	Tension	Compression	Tension	Compression
1	20.7 (3.0)		42.7 (6.2)		63 (6.2)	
2	46.9 (6.8)		100 (14.5)		152 (22.1)	
3	75.1 (10.9)		167 (24.3)		301 (43.7)	
4	70.3 (10.2)		149 (21.6)		208 (30.2)	
5	15.8 (2.3)		33 (4.8)		45 (6.5)	
6	106.9 (15.5)		232 (33.7)		38 (54.7)	
7	150.3 (21.8)		308 (44.7)		503 (73.0)	
8		14.8 (2.1)		32.4 (4.7)		47 (6.9)
9		2.7 (0.4)		4 (0.6)		3 (0.4)
10		18.6 (2.7)		41 (6.0)		73 (10.0)

Testing of a Heated Seal-End Model

For this work, the stainless steel model was equipped with electric resistance heaters and the seal edge was pressed directly against resistance heaters duplicating the contact of a seal edge and a

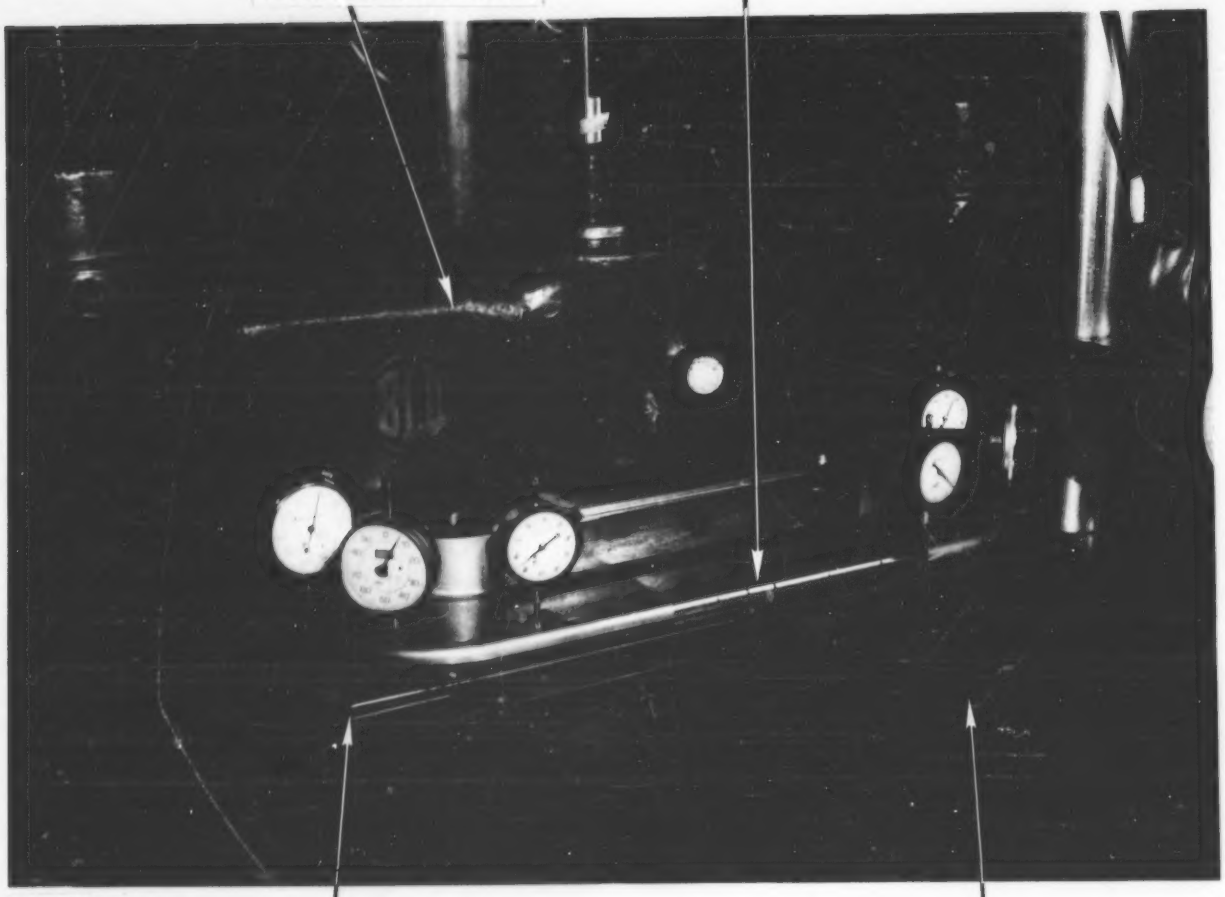


FIGURE IV-3. SEALING RING END SPECIMEN

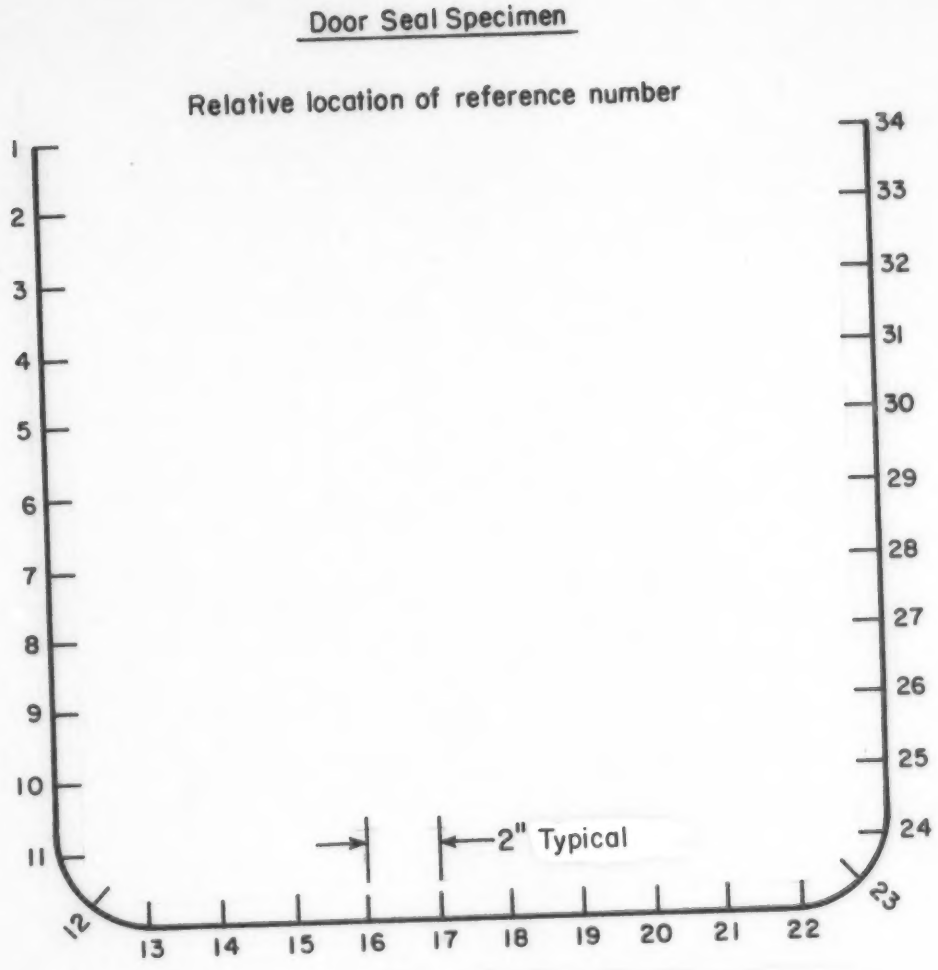


FIGURE IV-4. REFERENCE POINT ON END SPECIMEN SEAL

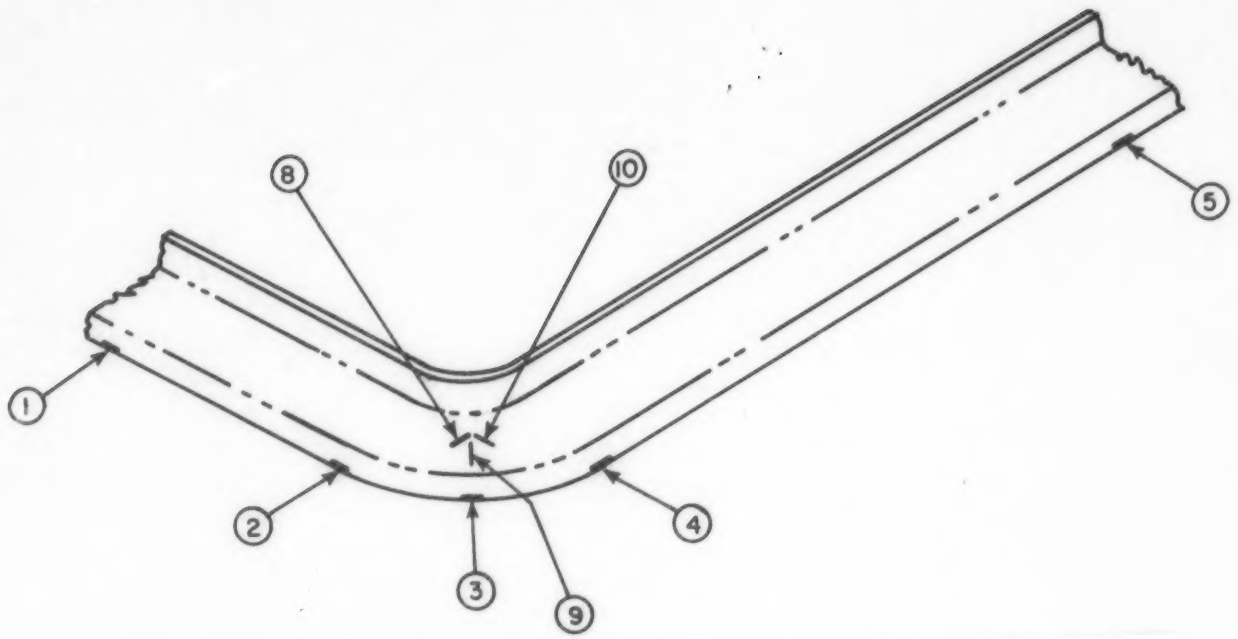


FIGURE IV-5. TOP VIEW SKETCH SHOWING THE LOCATION OF THE STRAIN GAUGES ATTACHED TO THE STAINLESS STEEL SEAL-END MODEL

Gauge Number	Reference Number–Gauge Location
1	17
2	22
3	23
4	24
5	29
8	Top. Parallel to side edge
9	Top. Parallel to 45 degree l
10	Top. Parallel to the bottom edge

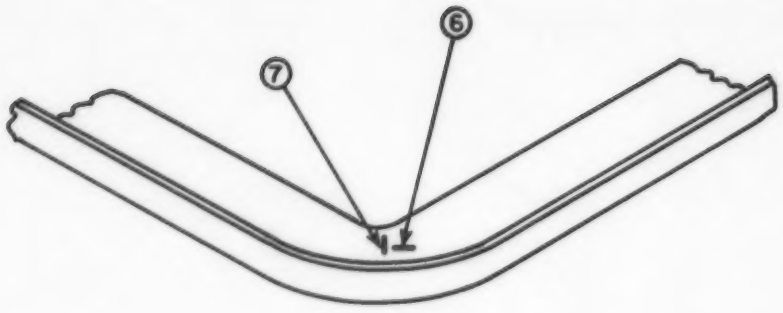


FIGURE IV-6. BOTTOM VIEW SKETCH SHOWING THE LOCATION OF STRAIN GAUGES 6 AND 7

Gauge 7 is parallel to the 45 degree line at the inner radius

Gauge 6 is normal to the direction of Gauge 7.

heated jamb. Strain gauge readings were converted to stress data including correcting the calibrated gauges for the temperature rise. Selected data are given as follows:

Seal Deflection	2.5 mm (0.1 in.)	2.5 mm (0.1 in.)
Deflection Loading	680 kg (1500 lb)	680 kg (1500 lb)

Strain Gauge Number	Temperature C	Temperature F	Calculated Stress Data in MPa and (Ksi) (thousands of pounds per square inch) Tension	Compression	Temperature C	Temperature F	Tension	Compression
1	24	75	42.7 (6.2)		164	328		124 (18.0)
2	24	75	100.0 (14.5)		183	361	101 (14.7)	
3	24	75	167.0 (24.3)		196	385	212 (30.8)	
4	24	75	149.0 (21.6)		186	366	120 (17.5)	
5	24	75	33.0 (4.8)		196	385		150 (21.8)
6	24	75	232.0 (33.7)		137	278	271 (39.4)	
7	24	75	308.0 (44.7)		137	278	203 (29.4)	
8	24	75		32 (4.7)	184	364		141 (20.5)
9	24	75		4 (0.6)	184	364	12 (1.7)	
10	24	75		41 (6.0)	184	364		167 (24.2)

Summary of the Inferences Taken from the Laboratory Test Data

The foregoing data and its possible implications were discussed with groups of laboratory personnel of appropriate disciplines. There was agreement that:

1. No conclusions could be drawn from these data.
2. The laboratory model was inappropriate (not valid) for additional testing.
3. Additional analytical testing should be done on a full-scale, complete ring seal made of Inconel X-750.

The model was considered inappropriate for additional work because it is only part of a complete seal, it is not made of the same material, and it was not produced by the same manufacturing methods. Using part of a seal allows the release of stress and/or does not allow the corners to react to stress transfer from another location on the seal. The stainless steel model could not be deflected to the same degree (without yielding) as the Inconel demonstration seals and it was considered possible that the "corner lift-off" effect (movement of the seal edge away from the jamb) only occurs at a high seal deflection level. The corners of the model were "hand made" whereas the demonstration seals corners were hydroformed. It was stated that the tests completed gave preliminary information on strains introduced as the result of loading, but gave no information on the residual stress (if any) in the corners and the interactions between the residual stresses and the loading stresses.

If was an internal recommendation that additional strain data (strain gauges and brittle lacquer approaches) should be obtained on a full-scale, complete sealing ring made of hardened Inconel, i.e., a complete demonstration seal. This was, however, beyond the limits of the available funds on this project.

The approach that was taken was to consider every practical change in the design of the corner that could possibly solve or alleviate the problem. The list of possibilities that came from discussions was as follows:

1. Remove the brake press-formed lip and install a demountable seal edge that can move/adjust laterally during the deflection of the seal, i.e, eliminate the high strain level in the lip (upstanding edge) during seal deflection.
2. Lower the resistance-to-deflection level of the corners (any method) to get increased flexibility. If necessary, depart from the original concept of "no backup springs" and install an external helper spring to force the corner seal edge against the jamb.

All of the above suggestions were considered and utilized in an empirically modified design of the demonstration seal. This redesign is presented in Chapter V of this report.

Summary of Work Completed at Republic Steel – Youngstown, Ohio

In March, 1980, four test seals were delivered to Republic Steel's coke batteries in Youngstown, Ohio. This shipment consisted of two coke and two pusher-side seals to be used in a combined demonstration and experimental effort.

The first step in the field work was to measure tha flatness of the seal edges. These measurements, unfortunately, revealed that the major flatness specification had not been met on any seal. Of the 16 corners on these 4 seals, 14 corners had a higher seal edge than other portions of the seal, i.e., the corners were high and would touch the jamb first with resulting gaps between the corners and above and below the corners. Of particular concern was the unevenness of the top and bottom portions of the seals. With a straight edge on the bottom portion of the seals, the gaps measured from 1 mm (0.040 in.) to 2.8 mm (0.11 in.).

In discussions between the fabricator and Republic Steel personnel, it was learned that (a) the fabricator was not in a position to grind the seals flat in a procedure recommended by Republic Steel and (b) the fabricator would remachine two seals in an effort to obtain a flat edge.

The remachining operation was observed by Republic Steel Engineering and Battelle personnel. It developed that machining is a slow and expensive operation that only resulted in some mild gains during machining. The approach used was to machine down the high portions of the seal using multiple, shallow passes with an end mill.

The decision was made to evaluate the reworked seal edges depending on the gaps remaining after "loading the seal" as if it were latched into place on an oven. For this operation, the seal was bolted to the work table in an upright position and a straight casting (plus weights) was placed on the seal until the total weight would deflect the entire seal a distance of about 7.6 mm (0.3 in.).

In this testing it was observed that:

1. A light loading of the seal for a deflection of only 0.7 mm (0.03 in. or 1/32 of an inch) indicated that there were no gaps around the top and bottom portion of the seal.
2. An overall seal deflection of 4.7 mm (0.185 in.) resulted in the beginning of gap formation at all corners.
3. A seal deflection with a 5440 kg load (12,000 lb) of 7 mm (0.28 in.) resulted in the formation of corner gaps of 0.05 mm (0.002 in.) to 0.2 mm (0.008 in.).
4. No amount of seal deflection, however, would eliminate gaps (between the seal edge and the flat table) along the *sides* of the seal. By design, this portion of the entire seal is the most flexible in terms of accommodation to minor unevenness in fabrication and any distributed unevenness or variation in the jamb surface. In this instance, there was variation from a plane surface of more than 1.6 mm in 1.2 meters (1/16 in. in 4 ft), i.e., more than the listed fabrication specifications. During seal loading tests, gaps remained in locations where the seal-edge height variations were extreme over a short distance, e.g., 1.5 mm in 30 cm (0.060 in. in 12 in.).

In the field work at Lackawanna, the probability of "corner lifting" was deduced from the test work and observation. In this instance, test work on a table permitted researchers to see and measure the corner lifting problem. Corner gaps from 0.05 mm to 0.2 mm might be acceptable from some points of view, but for the goal of "no gaps" (in this project), it was rated as unacceptable.

When it became apparent that the poorly fabricated seals could not be put into operating condition by machining at the fabricator, Republic Steel Engineering arranged to move a poor seal to Republic Steel's machine shop. There, with relative ease and in short order, the seal edge was *ground* completely flat.

The flat seal was placed seal-edge-down on a flat table and the seal was then deflected various distances using draw-down bolts and dial gauges to (a) simulate unheated response of the seal to deflection and (b) to measure any unusual response of the seal to deflection. The measurements taken on one end of the seal are given in Table IV-1. These data confirm the undesirable corner "lifting problem" and also appear to indicate that at least one corner was taking a "set" (plastic deformation) as a result of the seal deflection.

TABLE IV-1. CORNER MEASUREMENTS TAKEN ON A NEAR PERFECT SEAL (REPUBLIC STEEL – YOUNGSTOWN, OHIO)

Seal Deflection and/or Condition	Corner Gap Measurement	
	Left Side, in.	Right Side, in.
1. Start. No deflection, no load (Seal edge against flat table)	No gap	No gap
2. 0.060 in. seal deflection	0.002	0.002
3. 0.120 in. seal deflection	0.002+	0.002+
4. Return to start. No deflection	0.005	No gap
5. 0.200 in. seal deflection	0.005	0.003
6. 0.300 in. seal deflection	0.005	0.004
7. Return to start. No deflection	0.007	0.002
8. 0.030 in. seal deflection	0.005	No gap

Note: 1 inch = 25.4 mm.

Development of an Experimental Seal at Republic Steel

Test work at Battelle suggested that there may be advantages (or even a solution to the corner problem) if (a) the upstanding seal lip on demonstration seals were detachable or demountable and (b) steps were taken to increase the flexibility of corners in preparation for using backup spring force to keep the corners in contact with jambs.

One unsatisfactorily fabricated demonstration seal was selected for rework in Republic Steel's machine shop. This seal had been installed on a pusher-side door at the coke battery. When latched into place with a 0.2 in. seal deflection, only one corner sealed. The other three corners had about 0.15-mm (0.006-in.) gaps. The door was replaced before the coal was charged to the oven and the seal was removed and sent to the repair station. Here the following modifications were made by Republic personnel:

1. All the unstanding edges in the corners were removed to eliminate possible source of stiffness and/or reinforcement.
2. The flat portion of the seal in the lower corners only (Corners No. 1 and 2 in the following data) were saw cut on a 45 degree angle to attempt to relieve a possible stress concentration location. For comparative purposes the top corners (Nos. 3 and 4) were not slit or cut.
3. A 1/2 x 1/2 x 1/8-in. steel angle iron was bolted to the seal to act as a new (demountable) sealing edge. This angle iron was placed just inside the shorter existing seal and was carried around the corners from which the fabricated lip had been removed. The bending of the angle iron to form the 90 degree section around the corners resulted in some crimping of the angle iron (0.002 in. down from straight or flat) but this was not considered a problem.

After modification, the seal was taken to a 16-ft "run-out" table in Republic's machine shop. Deflection and measurement of the actions of this seal gave the following results:

1. With the seal edge (the 1/2 x 1/2 x 1/8-in. angle iron) against the table with no load, there were "huge" gaps at many locations. These were the result of the original improper fabrication. Practically all gaps along the side sealed during deflection. For example, a 0.6 mm (0.025 in.) gap was eliminated with a 5 mm (0.2 in.) forced deflection of the seal. In comparison, identical testing of a new standard S-shaped seal did not result in gap elimination of gaps initially (no load) as small as 0.05 mm (0.002 in.).
2. Concentrating on the problem corners, the following data were obtained during seal deflection.

2.0

Corner Gap at 45 Degree Location

Corner	1	2	3	4
Designation	Lower-Left	Lower-Right	Upper-Left	Upper-Right
Condition	Slit	Slit	No Slit	No Slit

Seal Deflection/Load

No load or deflection	0.079 in.	0.002 in.	0.063 in.	0.061 in.
5 mm (0.2 in.) deflection	0.002 in.	0.002 in.	0.002 in.	0.010–0.014 in.

Note: 1 inch = 25.4 mm.

3. Continued testing of the No. 4 corner above gave the following data.

Condition	Corner Gap
A. No load	0.061 in.
5 mm (0.2 in.) deflection	0.010 to 0.014 in.
7.6 mm (0.3 in.) deflection	0.008 to 0.009 in.
B. No load	0.061 in.
0.050 in. deflection	0.024 in. (Closure of 0.037 in. with deflection of 0.050 in.)
0.10 in. deflection	0.015 in. (Closure of 0.009 in. for additional 0.05 in. deflection)
0.15 in. deflection	0.010 in. (Closure of 0.005 in. for additional 0.050 in. deflection)
C. No load	0.061 in.
325 lb downward force (calibrated hydraulic piston)	0.024 in.
825 lb downward force	0.010 in.
2000 lb downward force	0.002 in.

Note: 1 inch = 25.4 mm
1 pound = .45 kg.

4. On slit corner No. 1, it only took 550 lb of downward force to close a gap of 0.079 in. (compared to about 2000 lb with an unslit corner).

   Comments:

   a. The 0.9 mm (0.037 in.) *partial* closing of a starting corner gap with only a slight deflection of the seal had been noted in the coke battery testing at Lackawanna. Also previously noted was the decreasing percentage of gap closure with increasing deflection. The same results were obtained with both the attached and the demountable seal edge indicating that the presence or absence of an attached upstanding lip may have little or nothing to do with the buildup of "resistance" in the corner with increased deflection.

   b. The "slit corners" appear to be more flexible than the unslit corners. This was regarded as a favorable inference with regard to the possibility of forcing the corners against the jamb.

Interruption of the Work at Republic Steel

After the testing period, it was found that funds were not available at Republic Steel (or Battelle) for (a) engineering and fabrication/installation of corner backup springs or for (b) grinding the seal edges flat, i.e., to remedy the problem forwarded from the fabricator. At a conference with the representatives of the sponsors (Mr. R. McCrillis of EPA and Mr. R. Phelps of Inland Steel representing the AISI) it was concluded that:

(a) It would be appropriate to ask a steel company other than Republic Steel for their contribution to the engineering/fabrication/installation of the backup corner springs on seal(s) of a modified design

(b) Demonstration work at Republic Steel should be held in abeyance until the corner-backup-spring approach could be tested at another location. Once confirmed and established, the concept could be transferred to the demonstration seals at Republic Steel at a minimum cost.

Mr. Phelps indicated that he would ask Inland Steel for clearance to do the needed fabrication/engineering/demonstration at Inland Steel Company. Inland had purchased sheets of Inconel X-750 during the period when the AISI officials were negotiating with seal fabricators.

Representatives of both sponsors expressed an interest in testing the modified design put forward by Battelle (see Chapter V). AISI/EPA/BCL agreed that:

(a) Switching to the modified seal represents a risk (because of unknowns) but it is a risk worth taking.

(b) All consideration of a mathematical analysis of the corner problem by Battelle should be held in abeyance to concentrate on plant fabrication and testing of the modified seal.

CHAPTER V

THE NEW SEAL DESIGN

At the start of this project, it was understood that the researchers would work towards analytically developing an improved and completely retrofittable seal without doing any empirical work or doing any preliminary field testing of seal designs. This meant that field problems had to be anticipated and resolved prior to any demonstration work. As indicated in Chapter IV of this report, we were not successful in anticipating all of the fabrication and performance problems encountered.

Permission was requested (and received) for the development/presentation of an empirical modification of the original design taking into consideration the insights developed and the suggestions received for improvement of the performance of the corners of the seal. This chapter deals with the background of this modification and presents a description of the new seal design.

Basis of the Redesign Effort

In reviewing the course of this project, it was decided that in the redesign, certain elements should be given special attention. These elements were as follows:

1. Revise the design to bypass all of the fabrication problems encountered.
2. If possible, modify the design to eliminate the need for seal fabricators having specialized equipment, i.e., attempt to develop a design that could be built by steel companies, if desired.
3. Accept more risk and step down from the use of expensive materials but retain the recommendation of using high-strength materials.
4. Incorporate the suggestions made by various researchers to improve the performance of the seal corners.
5. Partially relax, if necessary, our self-imposed dictum that "there shall be no adjustment devices or back-up springs behind the seal".

The New Design

The design that resulted is shown in cross section in Figure V-1. In this design, the spring element [market (A) in the figure] is a flat strip, cantilever-spring replacement for the formed S-shape spring used in the original design. This cantilever spring is bolted to a standard, heavy-section, carbon-steel angle iron [marked (B) in the figure].

It is recommended that the spring element should be made (and tested) using 17-4 PH stainless steel.(1) This alloy is available at a fraction of the cost of Inconel X-750 and was not considered in

(1) 17-4 PH is a trademark of Armco Steel Corporation.

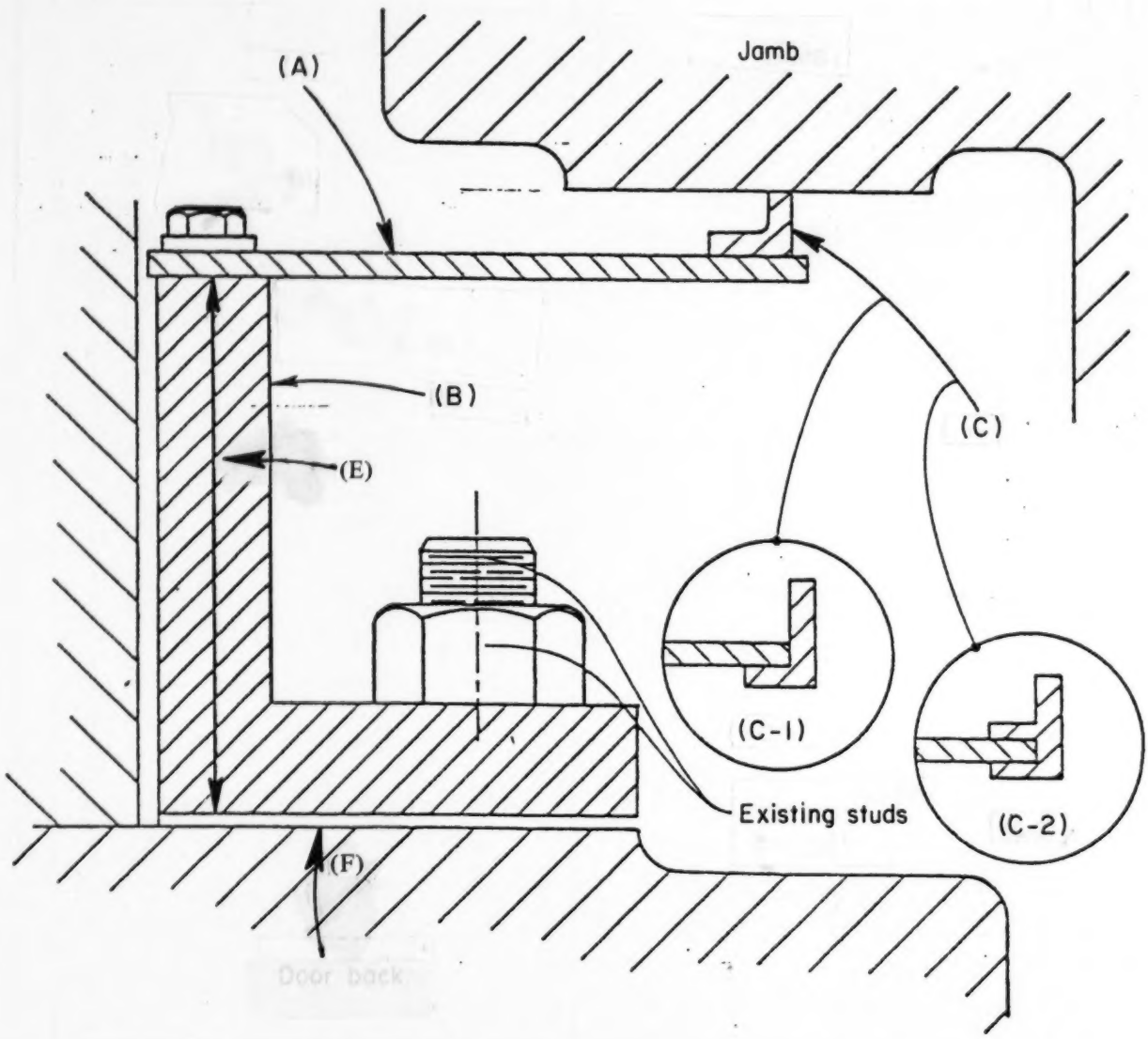


FIGURE V-1. CROSS SECTION OF A SUGGESTED NEW COKE-OVEN SEAL DESIGN

our original alloy selection process because it is relatively difficult to form. In this design modification, *all* forming operations have been eliminated and 17–4 is now the preferred candidate alloy. This alloy does not change its microstructure during any aging heat treatment and should not, therefore, warp during aging. As–received, annealed 17–4 PH has a yield strength (0.2 percent offset) of 1000 MPa (145 ksi) and a heat treated yield strength of up to 1275 MPa (185 ksi). It is possible that this alloy may be used without the need for any heat treatment.

The seal edge [marked (C) in the figure] is a demountable angle that is bolted or tack welded to the seal element. Other variations of this edge are shown in (C–1) and (C–2) in the figure. The load on this edge is low and carbon steel or stainless steel can be used depending on the corrosive action of the coal(s) being used in the ovens. The use of a standard shape for the seal edge should eliminate the need to machine or grind this edge flat after assembly. This assumption, however, remains to be tested.

The height of the leg of the angle–iron seal holder [marked (E) in the figure] can be varied depending on space considerations and on the need to bend this holder to form the seal edge to the profile of particular jambs. Spacers may be used below the holder [marked (F) in the figure] to "adjust" the holder profile during seal mounting. Gas tightness in this location can be assured by using carbon paste filler instead of gaskets below the seal holder.

Assembly of the New Seal

Figure V–2 is a front view of the new seal design. Worthy of note is that the rounded interior corners have been eliminated and we have returned to square interior corners. The outboard edge of the corner can be square or rounded depending upon the location of the door–mounted stop bolts. Figure V–3 illustrates a suggested cutting of stainless steel strip to develop the shape shown in Figure V-2. It is suggested that the 45 degree joints in the corners not be welded. It will be recalled that putting a 45 degree cut in the corner of a demonstration seal gave the indication that (a) the corner became less rigid, and (b) the corner became more amenable to contacting the jamb with the assistance of a spring–backup mechanism positioned only in the corners.

While not welding the spring strips in the corners is in line with our more favorable testing results, it introduces a potential leak or emission release location at each corner. For the initiation of field testing of this design, we are recommending the fastening of a piece of stainless steel foil covering the outboard side of the "slit" or junction. It remains to be seen whether this approach will handle what is an apparent problem.

For a period of time, we were thinking in terms of a radiused interior corner but Inland Steel personnel pointed out that the "slit" or unwelded corner junction eliminated the stress concentration effect that had caused Battelle to shift from a square corner to a rounded interior corner. With this logic, we agreed that a return to a simple square corner would be acceptable.

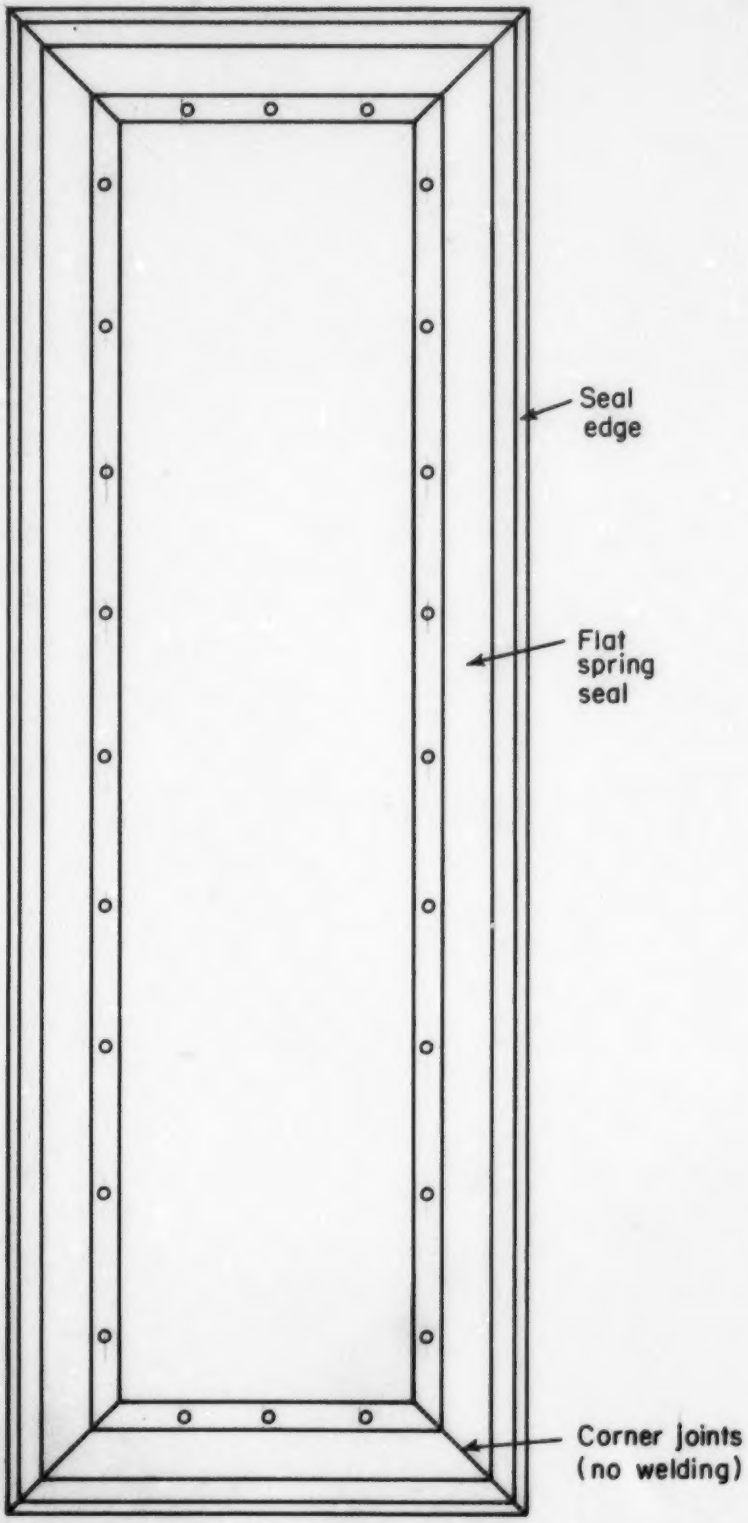
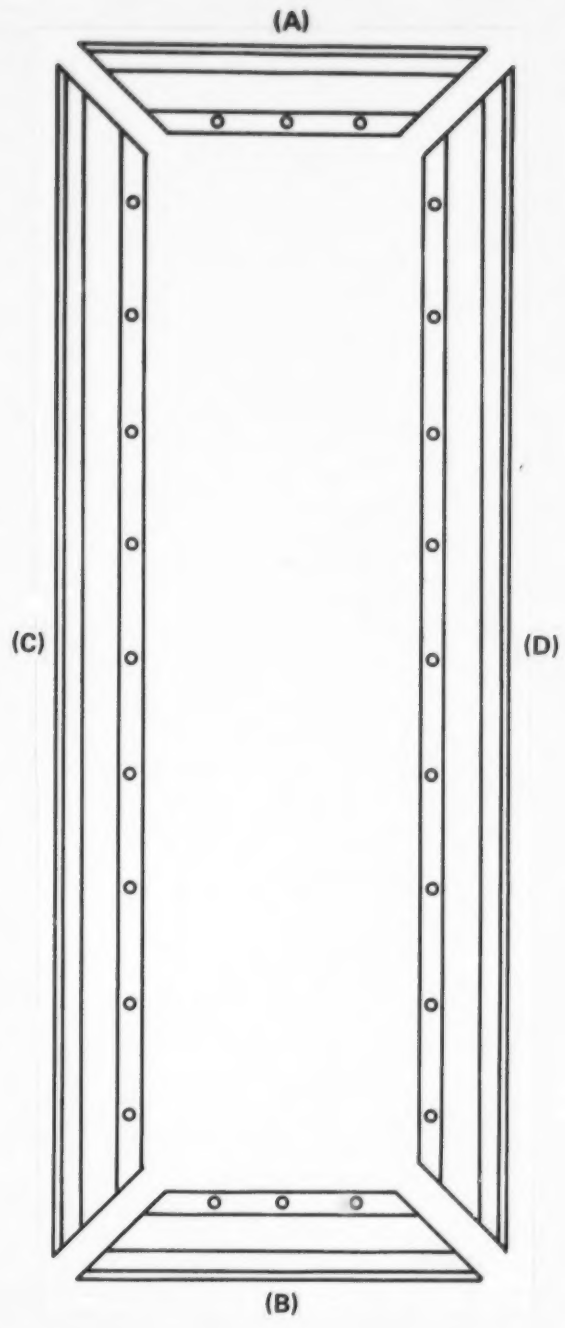


FIGURE V-2. FRONT VIEW OF THE SUGGESTED NEW SEAL DESIGN



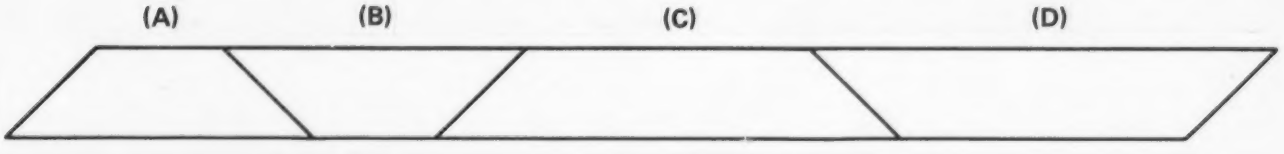


FIGURE V-3. SUGGESTED STRIP CUTTING TO FORM SEAL

It is expected that it will be necessary to force the corner of the seal against jambs using auxiliary spring force pressing against the outboard side of each corner. This auxiliary spring force can be delivered by a belleville-washer spring or an adaptation of the standard backup spring/plunger used on the standard S-shaped seal design. The amount of inward force required can be determined in the table testing of the first fabricated seal of this type. Based on the experience gained at Republic Steel, the "open" junction at the corners makes the seal corners very flexible, meaning that the additional force required to overcome "corner liftoff" is not expected to be high.

The above design incorporates all of the factors considered in the redesign. There are unknowns and qualifications in this design that can only be determined in field testing. For example, the shift from a curved spring element to a straight cantilever element results in a decrease in the effective width of the seal and in a concentration of stress at the fastening points. For these reasons it may be necessary to decrease the amount of allowable deflection of the seal on mounting the new-seal-equipped door on an oven. Also, it remains to be seen whether sealing problems will develop between the fastening points of the flat spring to the angle-iron holder and the seal edge to the flat spring. In this regard, it should be recalled that in coking coal, tar sealant is delivered to the seal on each and every coking cycle. This built-in sealing action may resolve any problems.

Present Status of the New Seal Design

In the initial attempts to obtain enough orders for demonstration seals to interest the standard fabricators of seals, several steel companies ordered Inconel X-750 sheets for use in fabricating demonstration seals. One of these companies was Inland Steel and this company has volunteered to engineer/fabricate/test and give oven trials to one seal. This seal is to be made of Inconel X-750.

The concept of having steel companies actively contribute to potential changes in their equipment and methods is much preferred over bringing in plans from the "outside". The NDGNIH (no good – not invented here) is strong in *any industry or organization* and it is powerful within the steel industry. One of the reasons this attitude exists is that credit is not given (internally or externally) for the improvements or industrialization of equipment and methods that have been completed within steel companies. In the instance of this new seal design, we wish to give advance credit if this approach is developed and industrialized. Based on our own experience, we know that having a plan or a design, and support by the superintendent, is just a start – the major effort and contributions have yet to come, and these efforts are sometimes more than difficult.

With the completion of our contract with AISI and EPA, we wish success to those that want to incorporate improvements into relatively fixed operations. Coke-door seals can be made to be practically emission free, but unfortunately only part of the answer lies in upgraded technology.